Punching Shear Resistance of Lightweight Concrete Offshore Structures for the Arctic: 1/25-Scale Model Study

David I. McLean
H.S. Lew
Long T. Phan
Hae In Kim

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
Gaithersburg, MD 20899

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

The punching shear resistance of lightweight concrete offshore structures for the Arctic is being investigated at the National Bureau of Standards on behalf of The Minerals Management Service of the U.S. Department of the Interior in cooperation with the following U.S. oil companies: Chevron Corporation, Exxon Production Research Company, Mobil Research and Development Corporation, and Sohio Petroleum Company. This report presents results of a 1/25-scale model study investigating the punching shear behavior of both plate and shell specimens. The study was undertaken to provide guidance for the selection of parameters for use in a larger, 1/6-scale, testing program. Initial tests on 1/6-scale plate specimens resulted in a complex combined punching and beam shear failure. The 1/25-scale models were capable of qualitatively replicating the failure mechanism that occurred in the initial 1/6-scale plate tests, and parameters were adjusted in the 1/25-scale specimens until a primarily punching shear failure was obtained in these specimens. Some quantitative agreement was also observed between the 1/25-scale and 1/6-scale tests. Recommendations are made for the 1/6-scale testing program.

Keywords: Arctic environment; experimental investigation; lightweight concrete; offshore structure; punching shear; reinforced concrete; small-scale model.

PREFACE

In 1984, a project was initiated at the National Bureau of Standards to study the performance of offshore concrete structures in the Arctic. An inital experimental program to study the punching shear behavior of lightweight concrete structures was developed with the financial and technical support of the following organizations:

- The Minerals Management Service, Department of the Interior;
- Chevron Corporation;
- Exxon Production Research Company;
- Mobil Research and Development Corporation;
- Shell Oil Company; and
- Sohio Petroleum Company.

The authors gratefully acknowledge the cooperation, support, and guidance provided by an advisory group formed by the project sponsors. The authors also acknowledge the consultation and technical contributions made to this project by Professor Richard N. White of Cornell University.

Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the sponsors of this project.

SI CONVERSION UNITS

In view of the present accepted practice in structural engineering, common units of measurements were used throughout this publication. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the International System of Units (SI) in 1960, the table below is presented to facilitate conversion to SI units.

TABLE OF CONVERSION FACTORS TO SI UNITS

	Customery Units	SI Units	Approx. Conversion
Length	inch (in)	meter (m)	1 in = 0.0254 m*
	foot (ft)	meter (m)	1 ft = 0.3048 m*
Area	in^2	m^2	1 in^2 = 0.000645 m^2
	ft^2	m^2	1 ft^2 = 0.0929 m^2
Force	pound (lbf)	newton (N)	1 lbf = 4.48 N
	kip	newton (N)	1 kip = 4.48 kN
Pressure or Stress	lbf/in^2 (psi)	N/m^2 (Pa)	1 psi = 6895 Pa
	kip/in^2 (ksi)	N/m^2 (Pa)	1 ksi = 6.895 MPa

* Exact

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The outer perimeter walls of Arctic offshore structures must withstand tremendous ice loads, and a possible failure mode of these walls is punching shear. Provisions in existing standards pertaining to punching shear resistance have been derived from tests on thin and lightly reinforced sections. The increased thickness, large amounts of both flexure and shear reinforcement, and the possible presence of in-plane compression resulting from arch action and prestressing brings into question the applicability of current code provisions. A major part of the current study is to investigate experimentally the punching shear resistance of heavily reinforced, high-strength, lightweight concrete slab and shell sections representative of structures proposed for use in the offshore regions of the Arctic.

For the main part of this experimental program, models with a scale factor of 1/6 were selected for study. In the course of selecting parameters, it became apparent that available analytical techniques were not adequate for predicting the ultimate strength behavior of the reinforced concrete test specimens. Yet, knowing the ultimate strength behavior of the specimens is vital (as was shown in the initial tests conducted on 1/6-scale specimens) in order to select parameters for a successful punching shear test. To gain this needed information on the ultimate strength behavior of the 1/6-scale specimens, a series of tests were conducted on 1/25-scale specimens.

1.2 OBJECTIVES AND SCOPE

The objectives of the 1/25-scale model study are:

1) to study the effect of various parameters on the failure mechanism in the specimens, and to gain increased insight into the nature of punching shear failures; and

2) to select parameters for use in the 1/6-scale testing program that will produce the desired punching shear mode of failure in the specimens.

Chapter 2 discusses results of two initial punching tests conducted on 1/6-scale plate specimens. The testing procedure for the 1/6-scale specimens is briefly reviewed. The mode of failure in the two specimens is discussed.

Chapter 3 presents details of the experimental program for the 1/25-scale specimens. Model materials, fabrication, and test setup are discussed.

Chapter 4 discusses the results obtained from the tests on the 1/25-scale specimens. A comparison is made between the initial 1/6-scale tests and a comparable 1/25-scale plate specimen. Results of the tests on a total of seven plates and three shells are presented.

Chapter 5 summarizes results of the 1/25-scale tests. Conclusions that were reached on the effect of parameters investigated in this study and recommendations for the 1/6-scale testing program are discussed.

CHAPTER 2

INITIAL 1/6-SCALE TESTS

2.1 INTRODUCTION

Before discussing the 1/25-scale testing program, results of two tests on 1/6-scale plate specimens are presented. These tests were originally conducted as part of the 1/6-scale testing program investigating punching shear strength. However, upon completion of these initial tests, it was observed that a clear-cut punching shear failure was not taking place in the specimens. Rather, a complex interaction of failure modes was occurring. This chapter presents details and results of the two initial 1/6-scale tests.

2.2 1/6-SCALE EXPERIMENTAL PROGRAM

Two general configurations of perimeter walls of Arctic offshore structures were targeted for investigation in this study: one with a flat outer surface and the other with a curved outer surface (see figure 2.1). For the flat wall configuration, a three-span section was isolated for study, with load being applied at the center of the middle span (figure 2.1). For the curved configuration, a single-span section was chosen with load being applied at the center of the span (figure 2.1).

A survey of available literature [1] indicates that spans in Arctic offshore structures range from 16 to 25 ft. Thicknesses of the perimeter walls vary from 2 to 5 ft, with the thicker dimensions occurring in structures with a flat wall configuration. Flexural reinforcing ratios range from 1 to 2.5 percent (each way and in each face), and shear

reinforcing ratios as high as 1 percent have been reported. For the initial 1/6-scale plate tests, the following prototype dimensions and reinforcing ratios were selected:

- a span of 20 ft;
- a wall thickness of 3.5 ft;
- a flexural reinforcing ratio of 2.5 percent; and
- for the initial tests, no shear reinforcement.

Selection of an area of loading for the specimens was based on consideration of several factors. The area of loading should be selected such that, at failure, the contact pressures are within the range of ice pressures that might develop on real structures (500 to 3500 psi [1]). The area of loading must also be selected so that a punching shear failure results and interaction with other failure modes is minimized. A prototype area of loading of 25 ft^2 was selected for the initial plate tests.

A detailed discussion of the procedure used for selecting the dimensions and boundary conditions of the test specimens and the area of loading to be used in the tests can be found in reference 2.

Since the intent of both the 1/6-scale and the 1/25-scale model studies is to observe the punching shear behavior of the plate and shell specimens through failure, ultimate strength models are required. Ultimate strength reinforced concrete models are geometrically similar to the prototype, both internally and externally, and loads must be applied to the models in the same manner as it is to the prototype. In addition, the model materials must simulate the inelastic, nonlinear compressive and tensile nature of the concrete and also the strength and bond characteristics of the steel

reinforcement. A discussion of general similitude theory and more detailed information on reinforced concrete models can be found in references 3-5.

A scale factor of 1/6 was selected for this experimental investigation. This scale allows conventional reinforcing steel to be used for the model reinforcement and Portland cement concrete for the model concrete. The model concrete for the 1/6-scale testing program consisted of the following:

Portland cement, Type I	800 lb/yd^3
Solite lightweight aggregate, 1/2 in maximum size, saturated, surface dry	1025 lb/yd^3
concrete sand	1025 lb/yd^3
Corrocem[1]	96 lb/yd^3
water	269 lb/yd^3
air-entraining agent	30 oz/yd^3

This mix results in a compressive strength of 7000 psi in about 14 days. Dimensions of the initial 1/6-scale plate specimens are given in figure 2.2. The specimens were tested using a large hydraulic testing machine with a 12 million-pound load capacity.

2.3 RESULTS AND OBSERVATIONS OF THE INITIAL 1/6-SCALE TESTS

Results of the two initial 1/6-scale plate tests are summarized in table 2.1. Figure 2.3 shows the underside and a cross-section across the transverse direction of one of the failed specimens. This figure shows only

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[1]Corrocem is a concrete additive manufactured by Norcem Concrete Products, Inc. of Long Island City, New York. The product is 85% by weight silica fume, and the remaining 15% is a proprietary additive used to improve workability.

one of the two specimens; however, no significant differences in the failure mechanism or crack patterns occurred in the two specimens.

Several observations can be made about the failed specimens:

1) Shear cracks produced by the load propagated along the flexural steel layers and came out the sides of the specimen rather than penetrating through to the bottom surface resulting in a partial delamination of the specimen along the reinforcing layers. This was probably a result of the large amount of flexural reinforcement present.

2) Cracks developed along the supports and intersected with the shear cracks developing around the concentrated load. This support interaction may have had an effect on both the failure load and the failure mechanism.

3) From an examination of the cracks in the failed specimens, it appeared that a complex combined punching and beam shear failure occurred. This probably caused the specimens to fail at a lower load than if only a punching shear failure had occurred.

The 1/25-scale testing program was initiated in an attempt to eliminate these deleterious aspects and to select parameters that would lead to a more clear-cut punching shear failure in the 1/6-scale specimens.

Table 2.1 Summary of Initial 1/6-Scale Plate Tests

Specimen No.	Area of Loading (in^2)	Flexural Reinforcing Ratio (%)	Shear Reinforcing Ratio (%)	Compressive Strength f'_c (psi)	Failure Load P_u (kips)	Normalized Shear Strength $P_u / (b_o d \sqrt{f'_c})$
1	138*	2.50	0	7400	127	4.25
2	100	2.50	0	7500	118	4.38

*Load was transferred through an outer cylinder in this test, resulting in the larger area of loading.

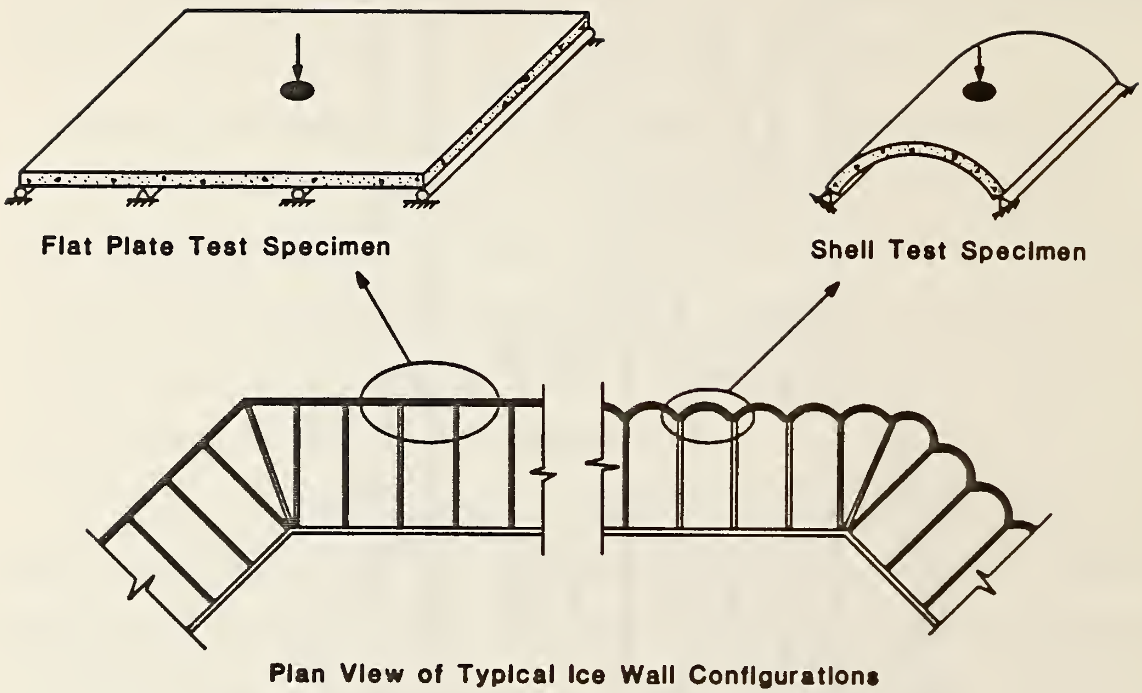


Figure 2.1 Concrete ice wall and test specimen configurations.

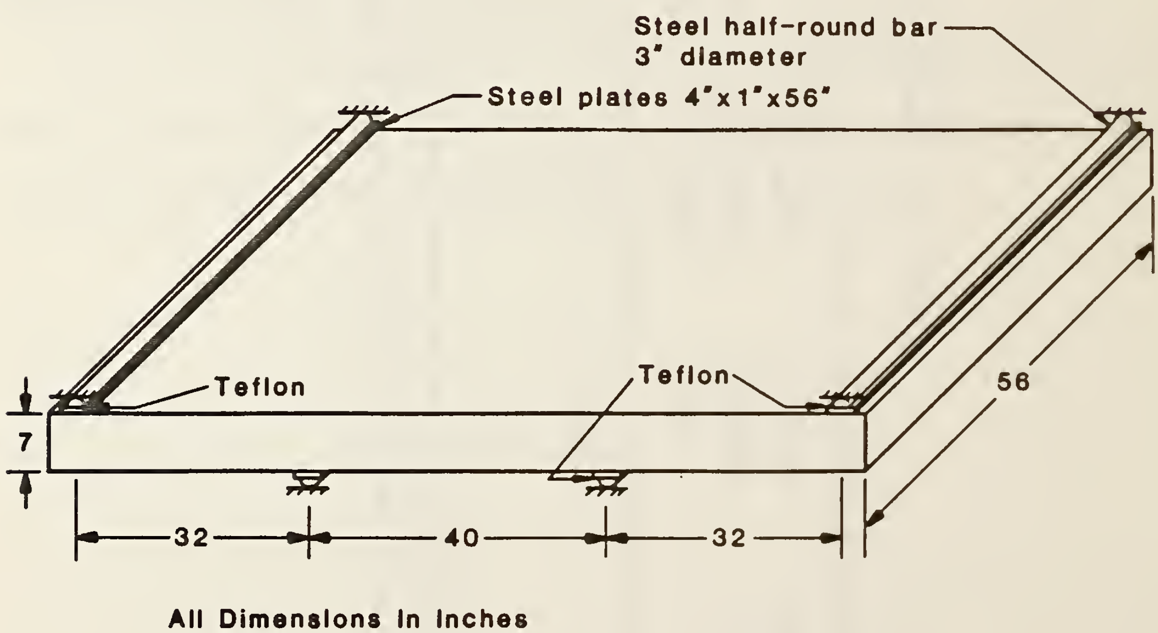
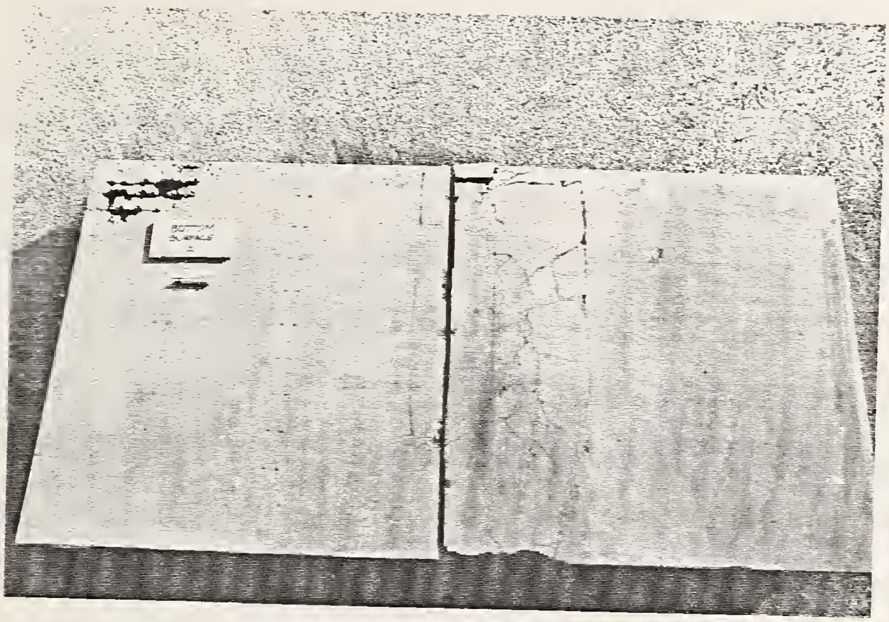


Figure 2.2 Initial 1/6-scale plate specimen dimensions.

(a)



(b)

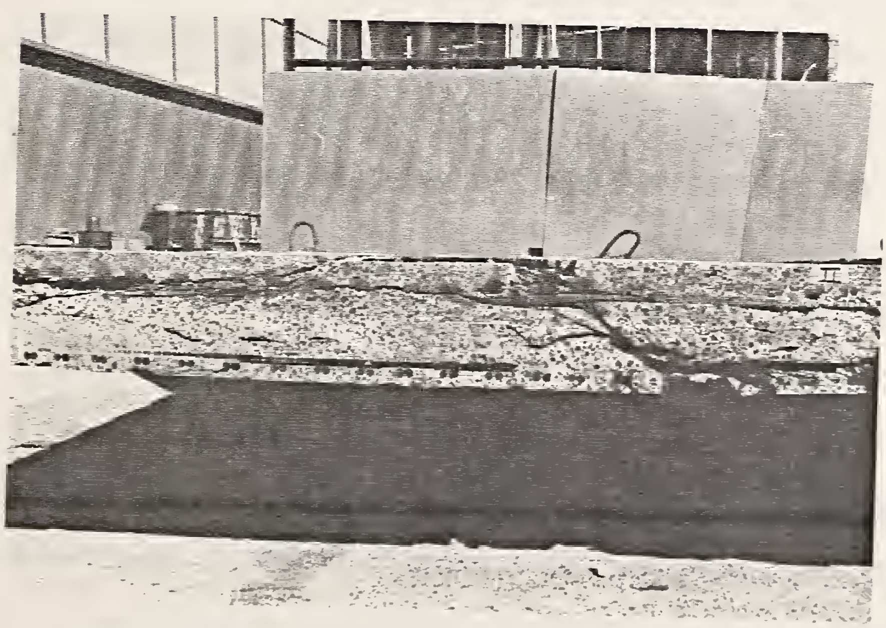


Figure 2.3 Cracks in a failed 1/6-scale plate specimen: a) underside; and b) transverse cross-section.

CHAPTER 3

1/25-SCALE EXPERIMENTAL PROGRAM

3.1 INTRODUCTION

The objectives of the 1/25-scale testing program are to study the effect of various parameters on the failure mechanism in the specimens and to provide guidance for the selection of parameters for the 1/6-scale tests. Both plate and shell 1/25-scale specimens were tested. The scale factor of 1/25 was selected to allow tests to be conducted on a much reduced scale, resulting in a savings of time and money. The 1/25-scale models should adhere to the same similitude requirements that were discussed in Chapter 2 for the 1/6-scale models. However, the 1/25-scale reinforced concrete models will exhibit significant size effects, limiting the applicability of numerical results from this study. These size effects are the reason it is necessary to test larger-scale models, i.e. 1/6-scale, in the main testing program. However, despite the fact that size effects are present, the objectives of the 1/25-scale study can be met by examining the results in a qualitative sense.

3.2 MODEL MATERIALS

3.2.1 Model Concrete

A gypsum model concrete was used for the 1/25-scale specimens. Gypsum concrete gives a reasonable representation of both the compressive and tensile properties of normal Portland cement concrete, but has the advantage of reaching the design strength 24 hours after casting. Further drying of the model results in a brittle behavior and thus the gypsum model must be

tested at 24 hours or the surface must be sealed to prevent drying from occurring beyond 24 hours. The model mix consisted of gypsum, sand, and water mixed in a ratio of 1:1:0.31, respectively. Sodium citrate was added as a retarder to increase working time. This mix resulted in a compressive strength of approximately 3000 psi. Compressive strengths were determined using 2 in by 4 in compressive cylinders tested at the same time as the specimen. A typical stress-strain curve is shown in figure 3.1.

The model concrete for the 1/25-scale specimens was different from the model concrete for the 1/6-scale specimens in at least three ways.

1) Gypsum was used instead of Portland cement. Apart from resulting in a lower compressive strength (see Item No. 3 below), use of gypsum probably did not result in any other significant differences in overall behavior.

2) Sand was used for the aggregate; there was no coarse aggregate, in particular, there was no lightweight coarse aggregate. Using only sand in the mix resulted in a different aggregate interlock component of shear transfer in the 1/25-scale models than was present in the 1/6-scale models.

3) The compressive strength of the 1/25-scale model concrete was approximately 3000 psi in comparison to 7000 psi for the 1/6-scale model concrete. This has the effect of lowering the apparent strength of the 1/25-scale models relative to the 1/6-scale models.

Additionally, size effects are greater in the 1/25-scale models, which, in contrast to Item No. 3 above, has the effect of increasing the apparent strength of the 1/25-scale models relative to the 1/6-scale models.

3.2.2 Model Reinforcement

Reinforcing steel in the 1/25-scale models consisted of commercially-

deformed, annealed wires with a diameter of 0.118 in (see figure 3.2). The yield stress of the wire, determined from tensile tests, was approximately 57 ksi. A typical stress-strain curve is shown in figure 3.3. The characteristics of the 1/25-scale model reinforcement were nearly identical to those of the ASTM Grade 60 reinforcing steel used in the 1/6-scale models.

3.3 FABRICATION OF THE SPECIMENS

The form for the plate specimens was made of high density, plastic coated plywood which was selected because of its strength, durability, non-stick properties, and machineability. The form was made to allow casting of the plate specimens in the horizontal position. The plywood was coated with a thin coat of oil to facilitate stripping of the form. Seven plate specimens were cast using the same form. Forms for the shell specimens were made from sections of Sonotube paper column forms of various radii. Casting of the shell specimens was in the vertical position. High density, plastic coated plywood was used for the bottom and sides of the forms. The inside of the forms was lightly coated with wax prior to casting. Each shell form could be used only once as stripping destroyed the forms. Forms for the compression cylinders were commercially-manufactured 2 in by 4 in paper molds coated with wax.

Curved reinforcement for the shell specimens was fabricated by bending the bars around a steel cylinder of approximately the same radius as that desired for the reinforcement. For both the plate and shell specimens, epoxy was used at the intersections of the steel bars to hold the cage

together. Spacers were used to position the steel layers in their correct location in the forms.

The gypsum model concrete was mixed in a small Hobart mixer. The wet concrete was immediately placed in the forms, and the forms were then vibrated externally with an electric vibrator. The forms were removed approximately 4 hours after casting, and 20 hours later the specimens were tested.

3.4 TESTING PROCEDURE

Tests on the 1/25-scale plate and shell specimens were performed using a Baldwin hydraulic testing machine at NBS. The test setup for the plate specimens is shown in figure 3.4. The interior supports for the plate specimens consisted of 1 in-diameter steel bars, while the outer supports consisted of 1 in-diameter half-round steel bars restrained with C-clamps to the testing table. A 0.75 in by 0.25 in steel plate was inserted between each support and the plate specimen to transfer the load from the specimen into the supports. Load was applied to the plate specimens through a steel cylinder, with a 0.125 in-thick layer of leather inserted between the cylinder and the specimen. This test setup was very similar to that used for the initial 1/6-scale plate tests.

The test setup for the 1/25-scale shell specimens is shown in figure 3.5. The specimens were tested in a specially fabricated testing frame. Three 0.75 in-thick steel plates were welded together to make the frame. Two 1 in-diameter steel bars were welded to the inclined plates to form the supports for the shell specimens. Steel angles, 0.25 in thick, were inserted between the round bars and the specimen to distribute load from the

supports into the specimen. Load was applied using the same system as was used for the plate specimens, except that the surface of the loading cylinder was machined to approximately the same radius as that of the shell specimen being tested. This test setup is similar to that anticipated for use in the 1/6-scale shell tests.

Deflections were monitored in both the plate and shell specimens using a dial gage. Rotations of the shell testing frame were monitored using an inclinometer.

After testing, the specimens were sectioned with a masonry saw to expose the internal cracking. The plate specimens were sectioned in the transverse direction at the centerline of the specimen. One of the remaining halves was then sectioned in the span direction along its centerline. The shell specimens were sectioned in the span direction at the centerline, and then one of the remaining halves was sectioned in the transverse direction.

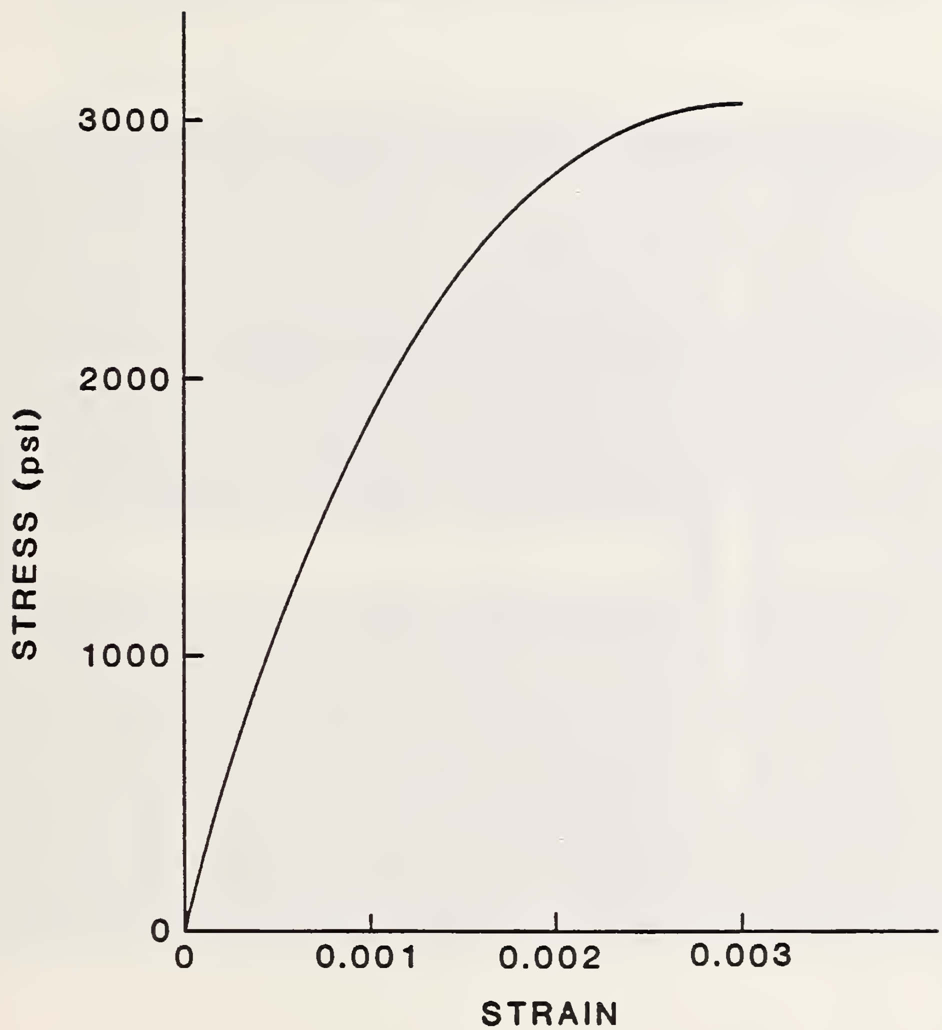


Figure 3.1 A typical stress-strain curve for the gypsum model concrete.

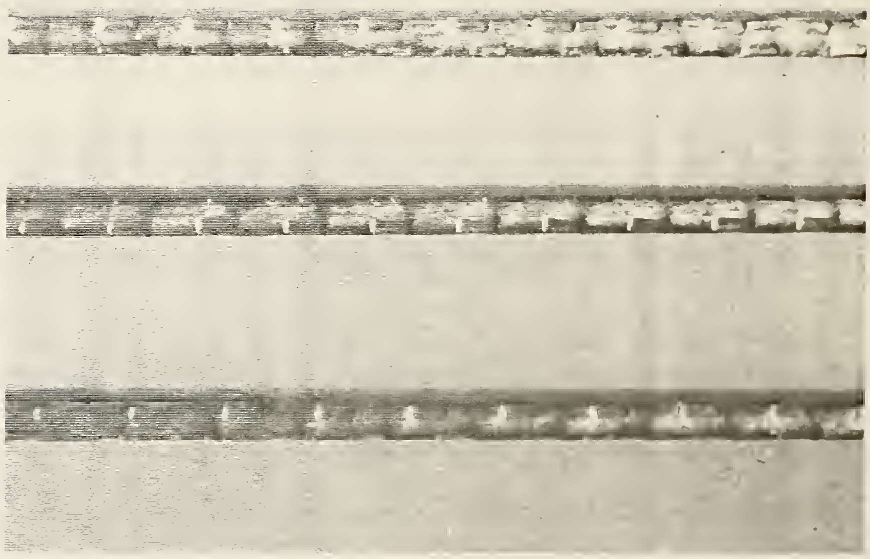


Figure 3.2 Close-up of the commercially-deformed model reinforcement showing the surface deformations.

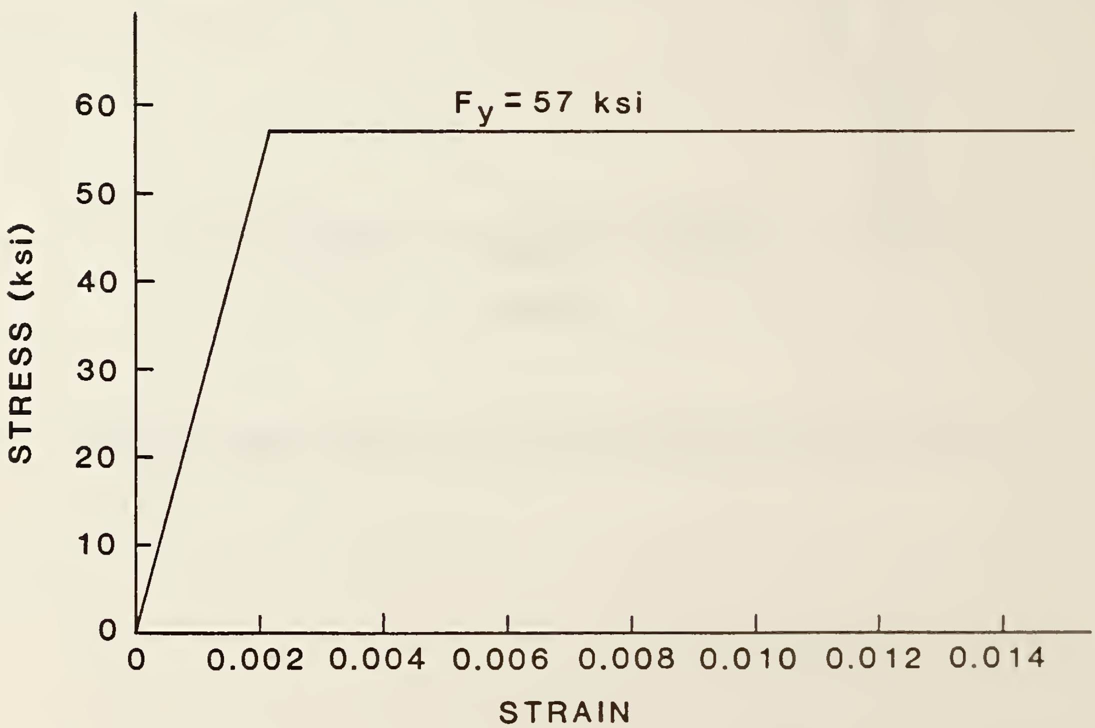


Figure 3.3 A typical stess-strain curve for the model reinforcement.

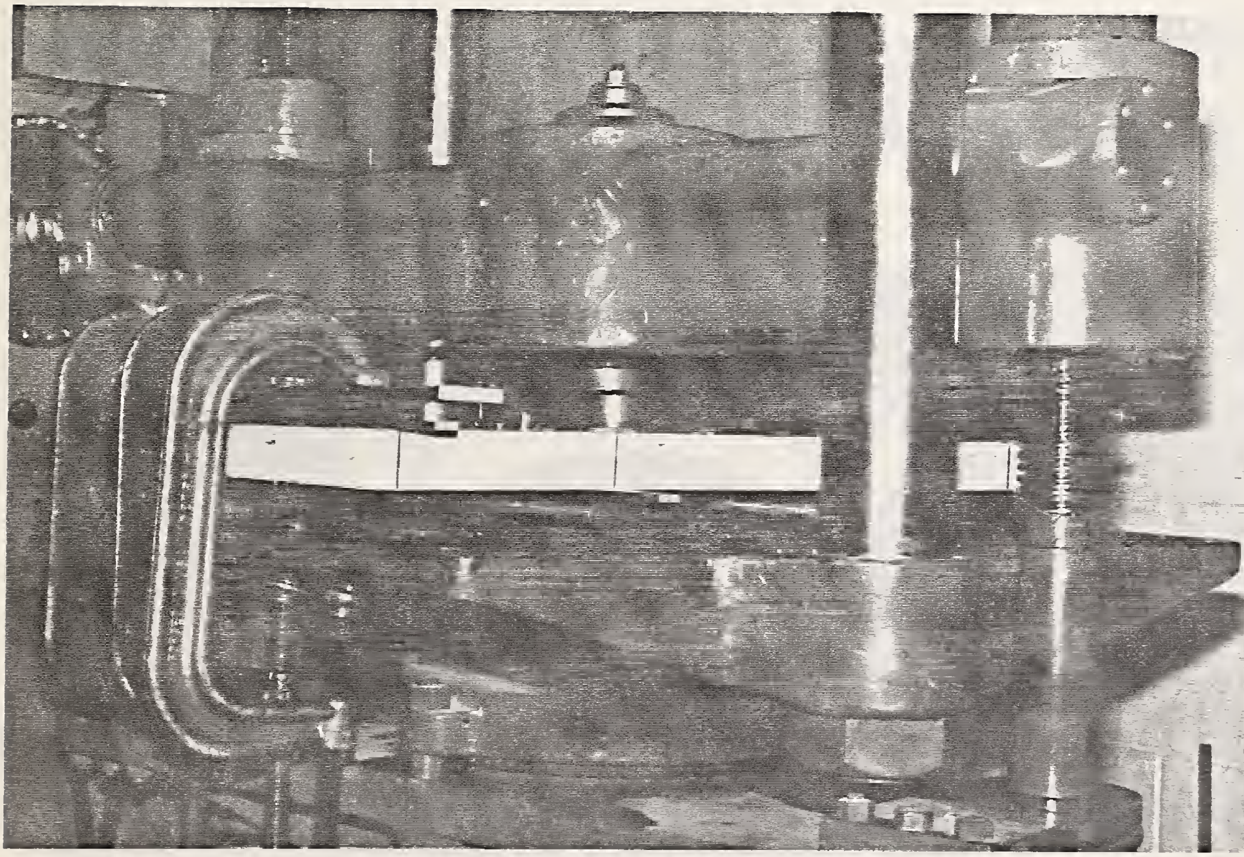


Figure 3.4 Test setup for the 1/25-scale plate specimens.

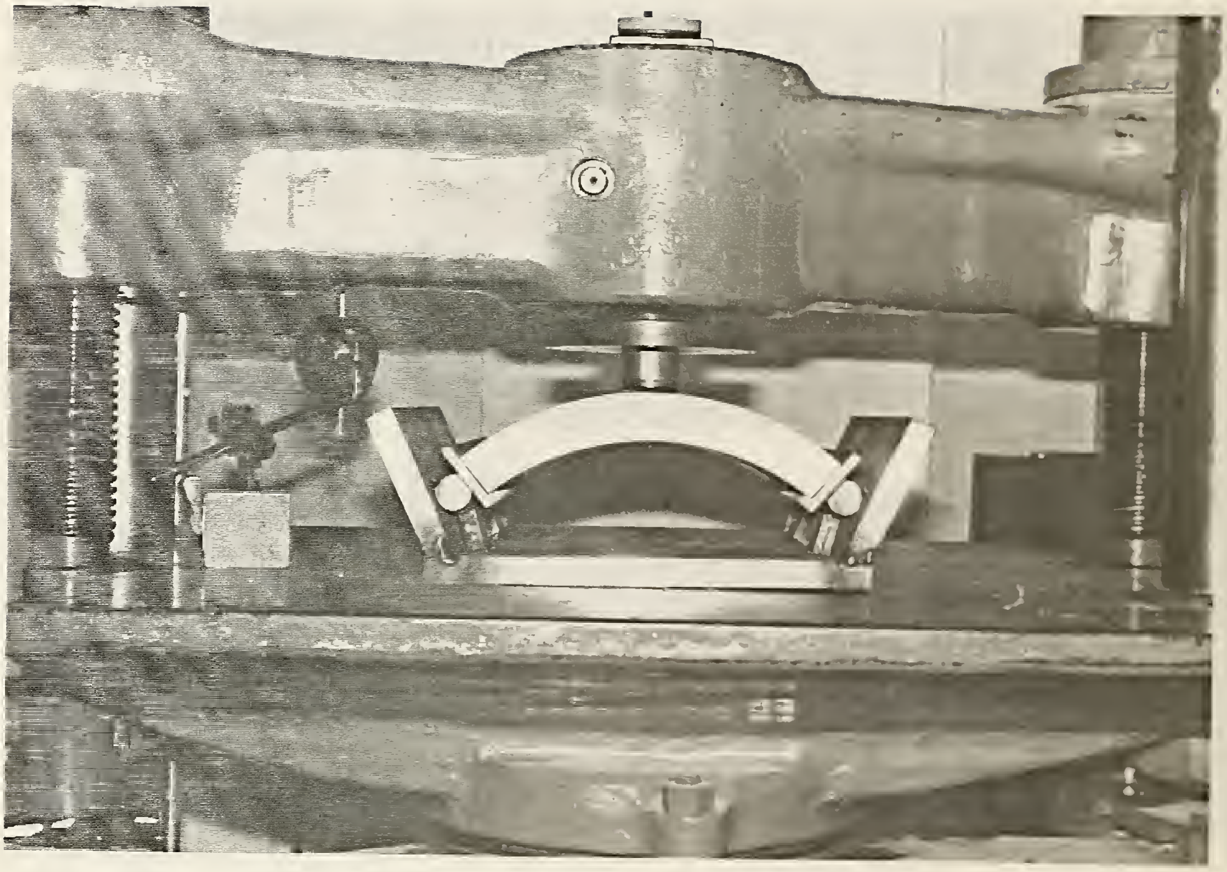


Figure 3.5 Test setup for the 1/25-scale shell specimens.

CHAPTER 4

1/25-SCALE TEST RESULTS

4.1 INTRODUCTION

This chapter presents results of the tests on the 1/25-scale specimens. A total of seven plate and three shell specimens were tested. However, before discussing these results, a comparison is made between the initial 1/6-scale tests and a comparable 1/25-scale plate specimen.

4.2 COMPARISON WITH THE INITIAL 1/6-SCALE TESTS

The first 1/25-scale plate specimen tested was a scaled version of the initial 1/6-scale specimens. The purpose of this first test was to see if a 1/25-scale specimen could replicate the failure mechanism that developed in the 1/6-scale specimens. Figure 4.1 shows the failed 1/25-scale plate specimen. Cracks propagated along the flexural steel layers and came out the sides of the specimen. Cracks developed along the supports interacting with the punching shear cracks, and a combined punching and beam shear failure appears to have occurred. Thus, at least in a qualitative sense, the failure mechanism was nearly identical to that observed in the 1/6-scale tests.

It is also interesting to note that the failure load for the 1/25-scale model was 7980 lb. Using similitude laws, this load can be scaled up to predict a failure load in a 1/6-scale specimen of 143 kips. In the actual 1/6-scale tests, the average failure load was 123 kips. Thus, in addition to qualitative agreement, some quantitative agreement also exists between the 1/25-scale and 1/6-scale tests. This quantitative agreement

should be viewed as more of coincidence than design. In general, small-scale reinforced concrete models, such as 1/25-scale, will not yield good numerical comparisons with prototype, or in this case larger-scale, tests.

4.3 RESULTS OF THE PLATE SPECIMEN TESTS

Results of the seven plate tests are summarized in table 4.1. The first specimen provided a comparison with the initial 1/6-scale tests and was discussed in the previous section; the remaining six plate specimen tests are discussed here.

In the second specimen tested (Specimen No. 2), the width of the specimen was increased to investigate if this prevented the cracks from propagating along the steel layers to the sides of the specimen. Figure 4.2 shows the failed specimen. Cracks penetrated through the top layer of steel, but propagated towards the sides of the specimen when they reached the bottom layer of steel. Cracks developed along the supports, and a combined punching and beam shear failure still occurred.

In Specimen No. 3, the area of loading was reduced by 36 percent (corresponding to a change from 25 ft^2 to 16 ft^2 in a prototype structure). Decreasing the area of loading physically increases the distance from the load to both the supports and the sides of the specimen. Decreasing the area of loading also lowers the load at which a punching shear failure will occur since the critical surface is decreased when the loaded area is decreased. In contrast, beam shear capacity is not dependent on the area of loading. Thus, decreasing the area of loading reduces the contribution of beam shear effects to the failure mechanism. The failed Specimen No. 3 is shown in figure 4.3. Cracks propagated along the bottom layer of steel and

developed at the supports, and there is evidence that a combined punching and beam shear failure still took place.

To see if increasing the span would reduce the influence of the supports on the development of shear cracks, Specimen No. 4 was tested with a span that was 25 percent larger than the span of Specimen No. 3 (corresponding to a change from 20 ft to 25 ft in a prototype structure). Figure 4.4 shows the failed specimen. The shear cracks did not propagate directly to the supports, as was observed in previous specimens. However, the cracks still penetrated through to the bottom of the specimen at the supports. Cracks in the transverse direction still propagated along the bottom layer of steel.

The flexural reinforcing ratio in Specimen No. 5 was reduced from 2.5 percent to 1.5 percent to investigate if this would allow the shear cracks to penetrate through the bottom layer of steel. The failed specimen is shown in figure 4.5. Shear cracks did penetrate through to the bottom of the specimen in some locations, which was an improvement over the previous tests. However, cracks still developed along the supports. It is interesting to note that no yielding of the reinforcement was evident prior to the shear failure (see the load-deflection curve for this specimen in figure 4.16).

In Specimen Nos. 6 and 7, all parameters and dimensions were the same as those of Specimen No. 5, except that the area of loading was reduced by an additional 38 percent (corresponding to a reduction from 16 ft^2 to 10 ft^2 in a prototype structure). The difference between Specimen Nos. 6 and 7 was in the loading procedure. Loading was stopped immediately after the first drop in load occurred for Specimen No. 6, while in Specimen No. 7, loading

was continued beyond the peak load until the load decreased to approximately half the peak load. This difference in loading procedure was done to study the order of crack formation in the specimens.

Specimen No. 6 is shown in figure 4.6. Shear cracks in the span direction penetrated through to the bottom of the specimen away from the supports. However, cracks in the transverse direction did not reach the bottom of the specimen. That the cracks were more developed in the span direction may indicate that, at least initially, more load is being carried in this direction. Figure 4.7 shows Specimen No. 7. Cracks penetrated through to the underside of the specimen, approximately forming the outline of the plug typical of a punching shear failure.

4.4 RESULTS OF THE SHELL SPECIMEN TESTS

Results of the three shell tests are summarized in table 4.1. The first shell specimen tested, Specimen No. 8, was constructed with a radius-to-thickness ratio (R/t) of 6 and a thickness the same as that of the plate specimens (corresponding to a 42 in-thick wall in a prototype structure). The failed specimen is shown in figure 4.8. Cracks in the span direction propagated away from the load along the top layer of steel on one side and along middepth to the support on the other side. Cracks in the transverse direction propagated away from the load to the bottom layer of steel, and then propagated out to the sides of the specimen. No cracks penetrated through to the bottom surface. Failure in this specimen was not primarily in punching shear.

Specimen No. 9 was identical to Specimen No. 8 except that the

thickness was reduced by 29 percent (corresponding to a change from 42 in to 30 in for a prototype structure). Figure 4.9 shows the failed specimen. Cracks penetrated through to the bottom of the specimen, forming the outline of a plug. Specimen No. 10 was constructed with the same thickness as Specimen No. 9, but with an R/t of 12. Figure 4.10 shows the failed specimen, and cracks have also penetrated through to the bottom surface of this specimen.

4.5 OTHER OBSERVATIONS

In the summary of the test results listed in table 4.1, the contact pressure at the ultimate load is listed for each specimen. For the plate specimens, figure 4.11 shows the variation in contact pressure with changes in the area of loading. The contact pressure decreases with increasing area of loading.

The normalized shear strength of each specimen is also listed in table 4.1. While numerical results of the 1/25-scale tests must be viewed with caution, a trend in the normalized shear strength was observed. The shear strength for the plate specimens varies from 8.2 to 9.6, while for the shell specimens it varies from 11.6 to 12.1. The higher values of normalized shear strength observed in the shell specimens are a result of arch action introduced by the shell geometry.

It was observed in many of the 1/25-scale specimens that cracks intersected with reinforcement running perpendicular to the direction of crack development. That is, the reinforcement appears to have acted as a stress raiser, particularly in the region underneath the applied load,

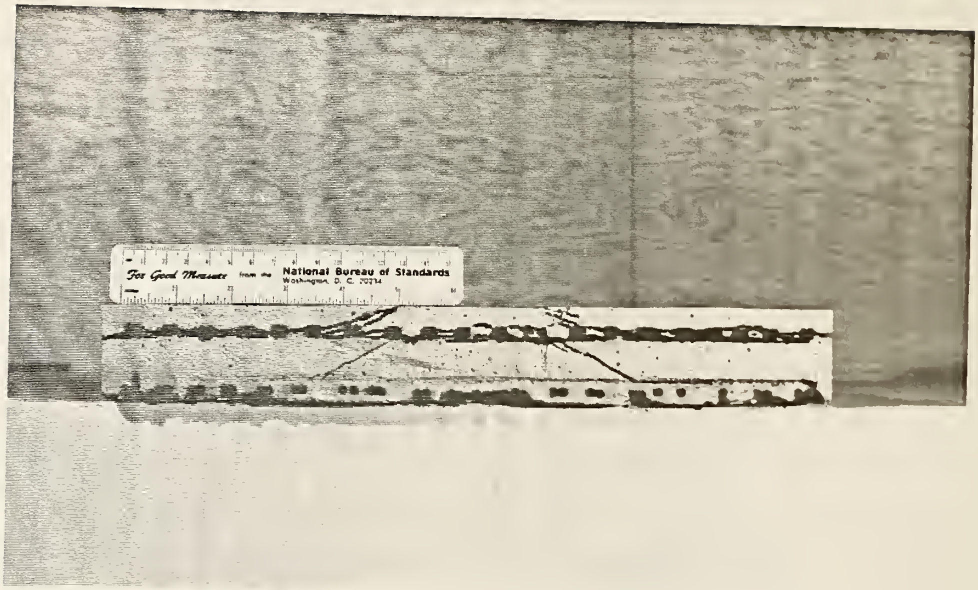
influencing the location and direction of crack development. Some evidence of this phenomenon is also visible in the 1/6-scale tests.

Load-deflection curves for the specimens are given in figures 4.12-4.21.

Table 4.1 Summary of 1/25-Scale Tests

Model No.	Geometry	Wall Thickness (in)	Specimen Width (in)	Span (in)	Flexural Reinforcing Ratio (%)	Area of Loading (in^2)	R/t	Central Angle (°)	Compressive Strength f'_c (psi)	Failure Load P_u (lb)	Normalized Shear Strength $P_u / (b_o d \sqrt{f'_c})$	Contact Pressure (psi)
1	plate	1.65	13.22	9.44	2.50	5.57	-	-	2300	7980	9.3	1430
2	plate	1.65	18.88	9.44	2.50	5.57	-	-	2650	7700	8.4	1380
3	plate	1.65	13.22	9.44	2.50	3.56	-	-	2800	7460	9.1	2090
4	plate	1.65	13.22	11.80	2.50	3.56	-	-	2300	6095	8.2	1700
5	plate	1.65	13.22	9.44	1.50	3.56	-	-	2950	7480	8.9	2100
6	plate	1.65	13.22	9.44	1.50	2.23	-	-	2750	6500	9.1	2940
7	plate	1.65	13.22	9.44	1.50	2.23	-	-	2500	6500	9.6	2940
8	shell	1.65	13.22	9.44	1.75	2.23	6	56.9	3250	9000	11.6	4070
9	shell	1.18	13.22	9.44	1.75	2.23	6	83.6	3150	5270	12.1	2380
10	shell	1.18	13.22	9.44	1.75	2.23	12	38.9	3150	5090	11.7	2300

(a)



(b)

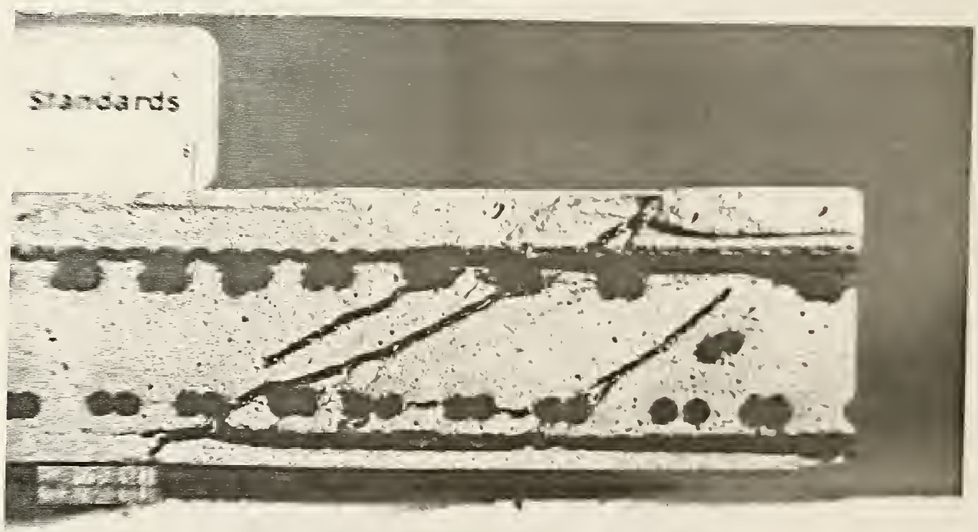
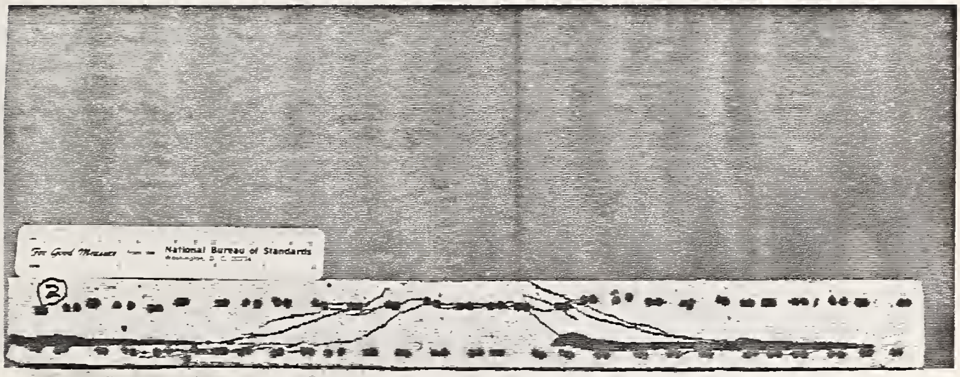


Fig. 4.1 Cracks in specimen no. 1: a) transverse cross-section; and b) span cross-section on half the specimen.

(a)



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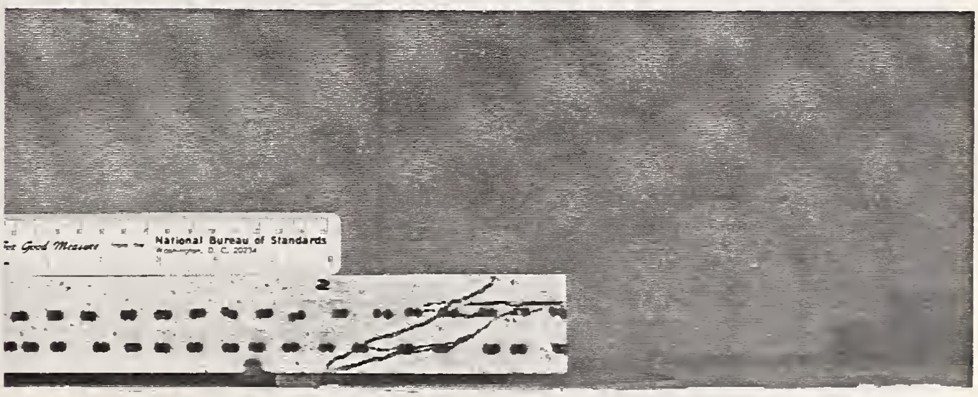
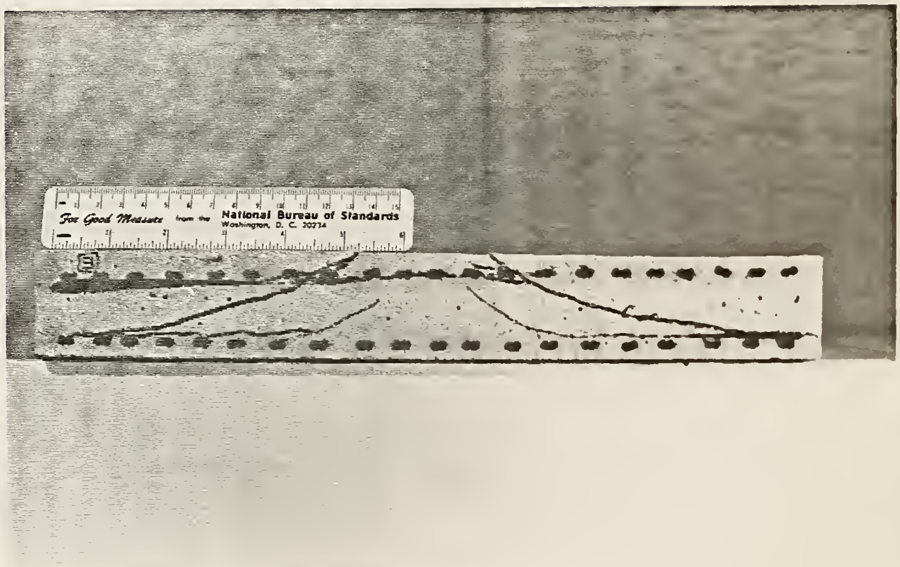


Fig. 4.2 Cracks in specimen no. 2: a) transverse cross-section; and b) span cross-section on half the specimen.

(a)



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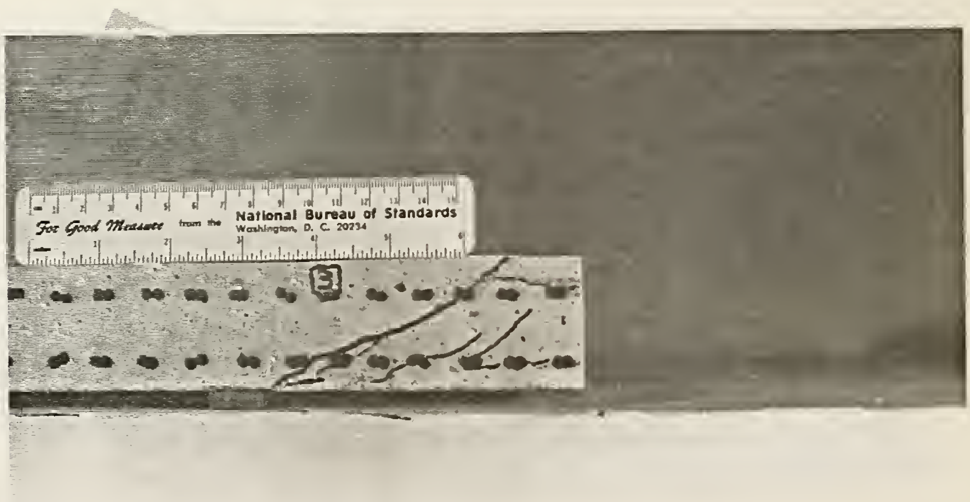
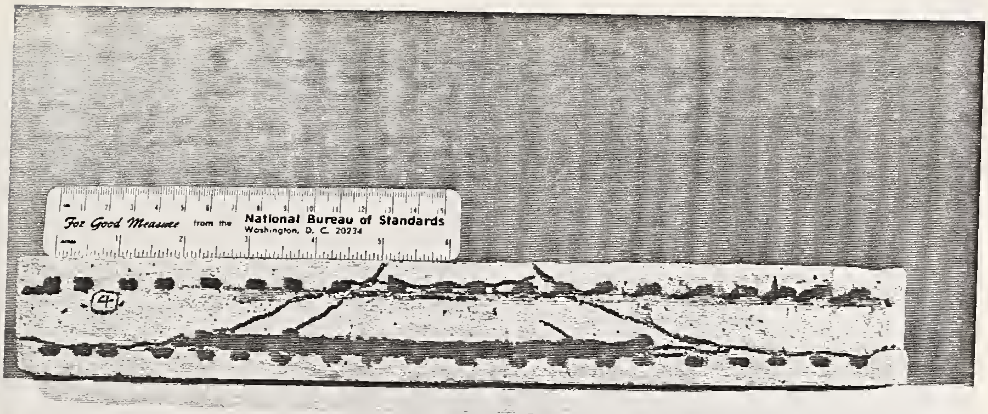


Fig. 4.3 Cracks in specimen no. 3: a) transverse cross-section; and b) span cross-section on half the specimen.

(a)



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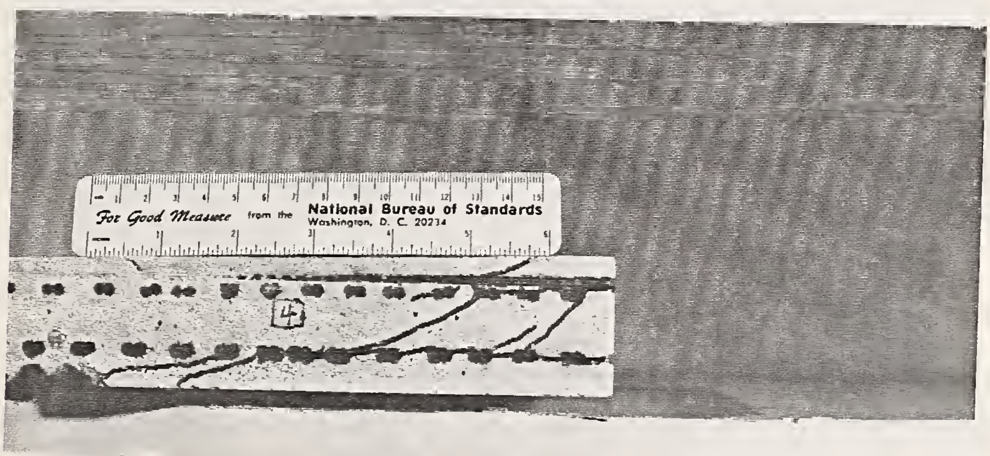
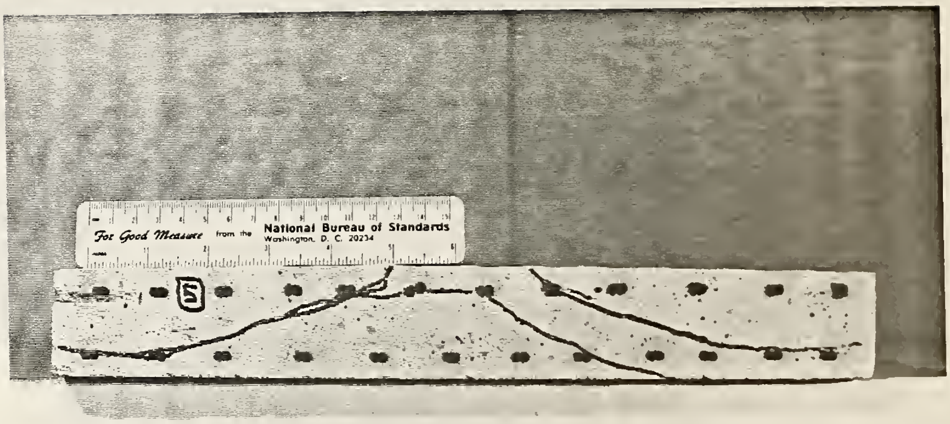


Fig. 4.4 Cracks in specimen no. 4: a) transverse cross-section; and b) span cross-section on half the specimen.

(a)



(b)

Fig. 4.5 Cracks in specimen no. 5: a) transverse cross-section; and b) span cross-section on half the specimen.

(a)

(b)

(c)

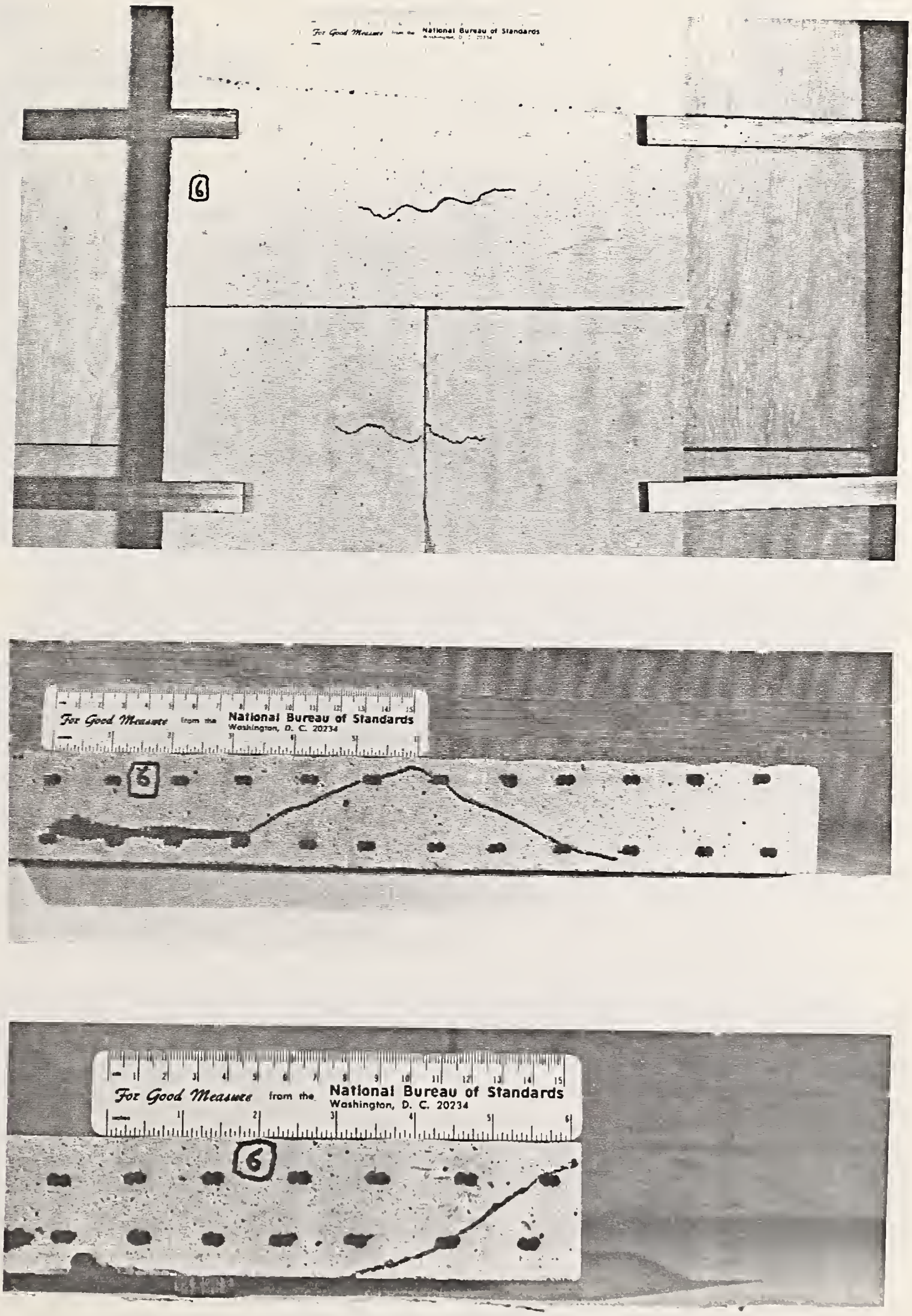
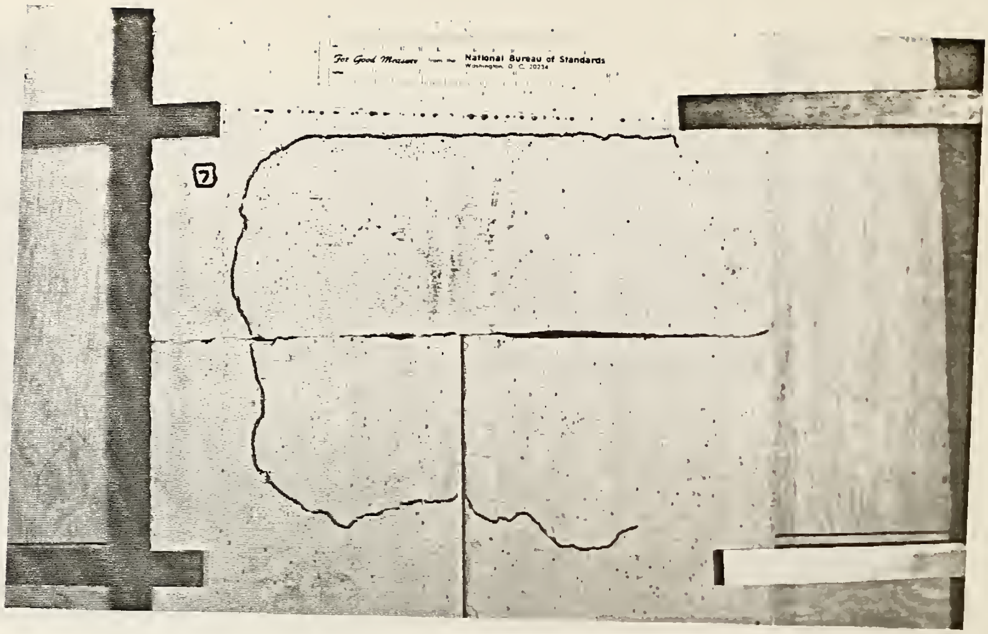
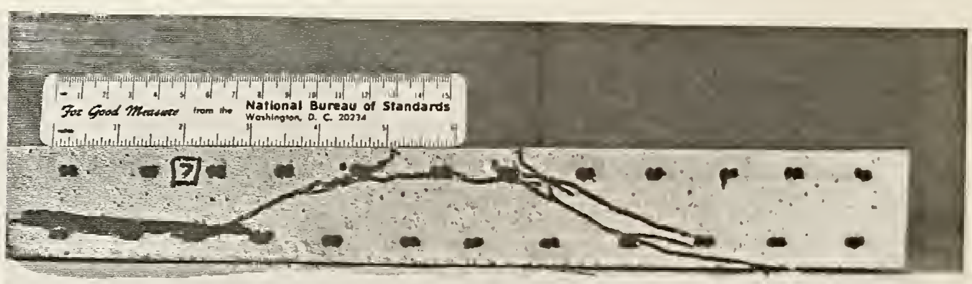


Fig. 4.6 Cracks in specimen no. 6: a) underside; b) transverse cross-section; and c) span cross-section on half the specimen.

(a)



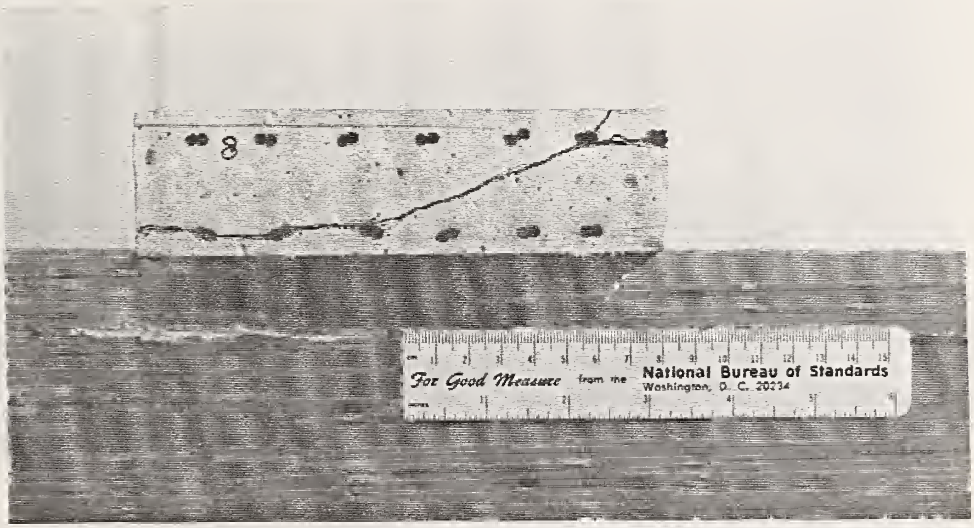
(b)



(c)

Fig. 4.7 Cracks in specimen no. 7: a) underside; b) transverse cross-section; and c) span cross-section on half the specimen.

(a)



(b)

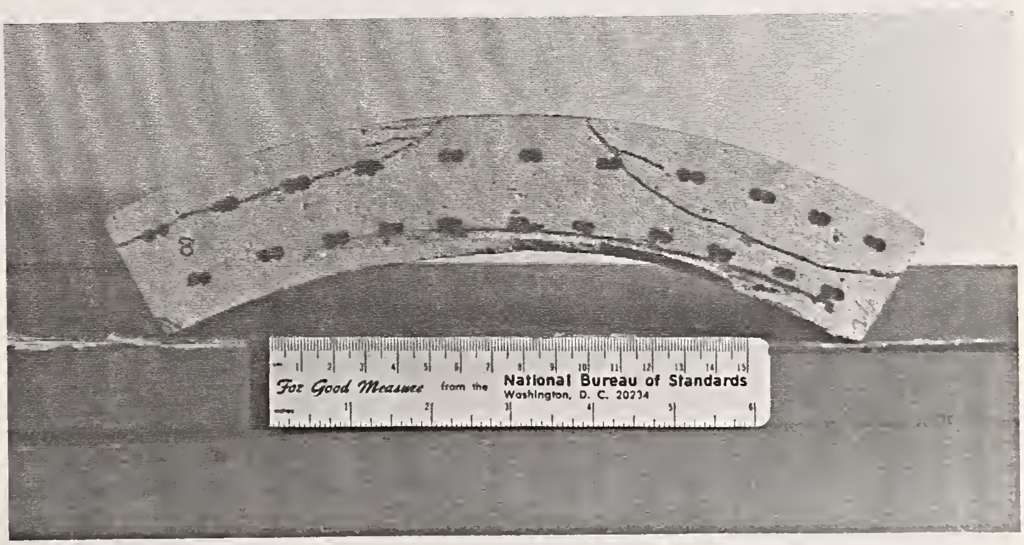
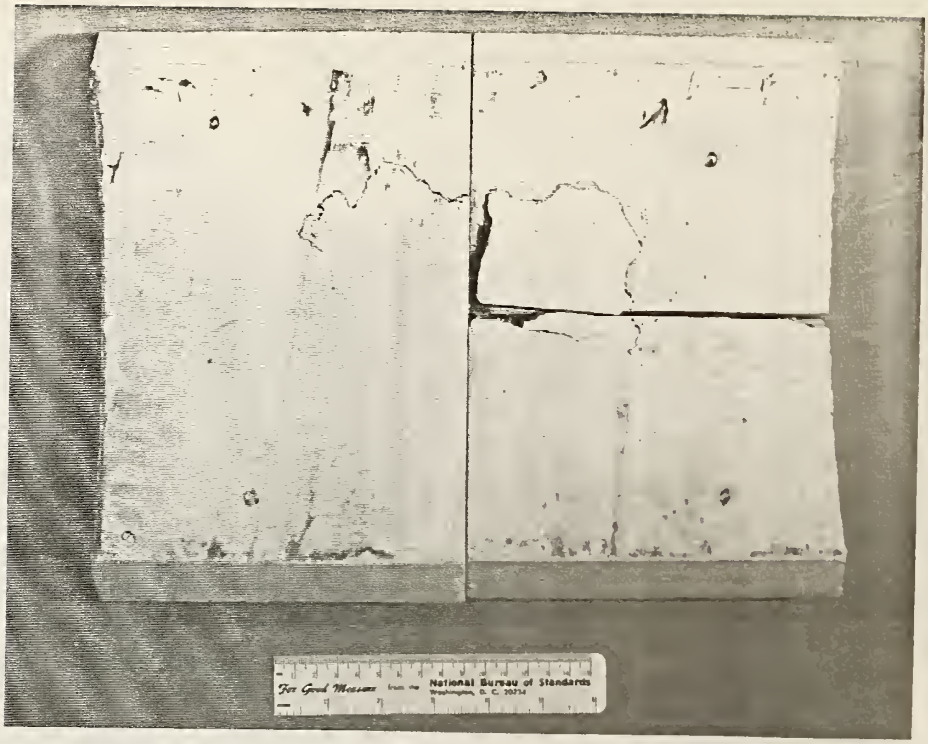
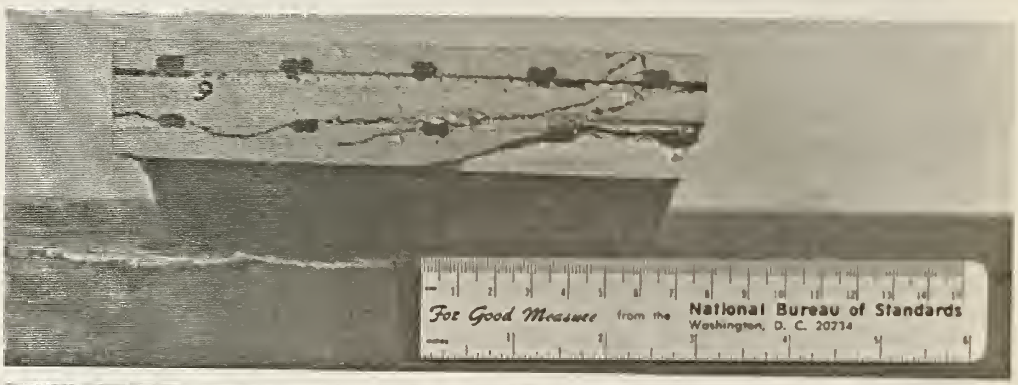


Fig. 4.8 Cracks in specimen no. 8: a) transverse cross-section on half the specimen; and b) span cross-section.

(a)



(b)



(c)

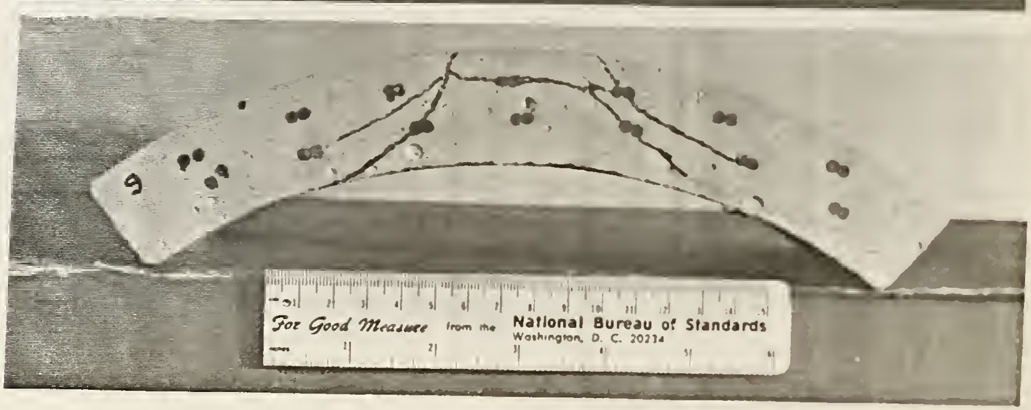


Fig. 4.9 Cracks in specimen no. 9: a) underside; b) transverse cross-section on half the specimen; and c) span cross-section.

(a)

(b)

(c)

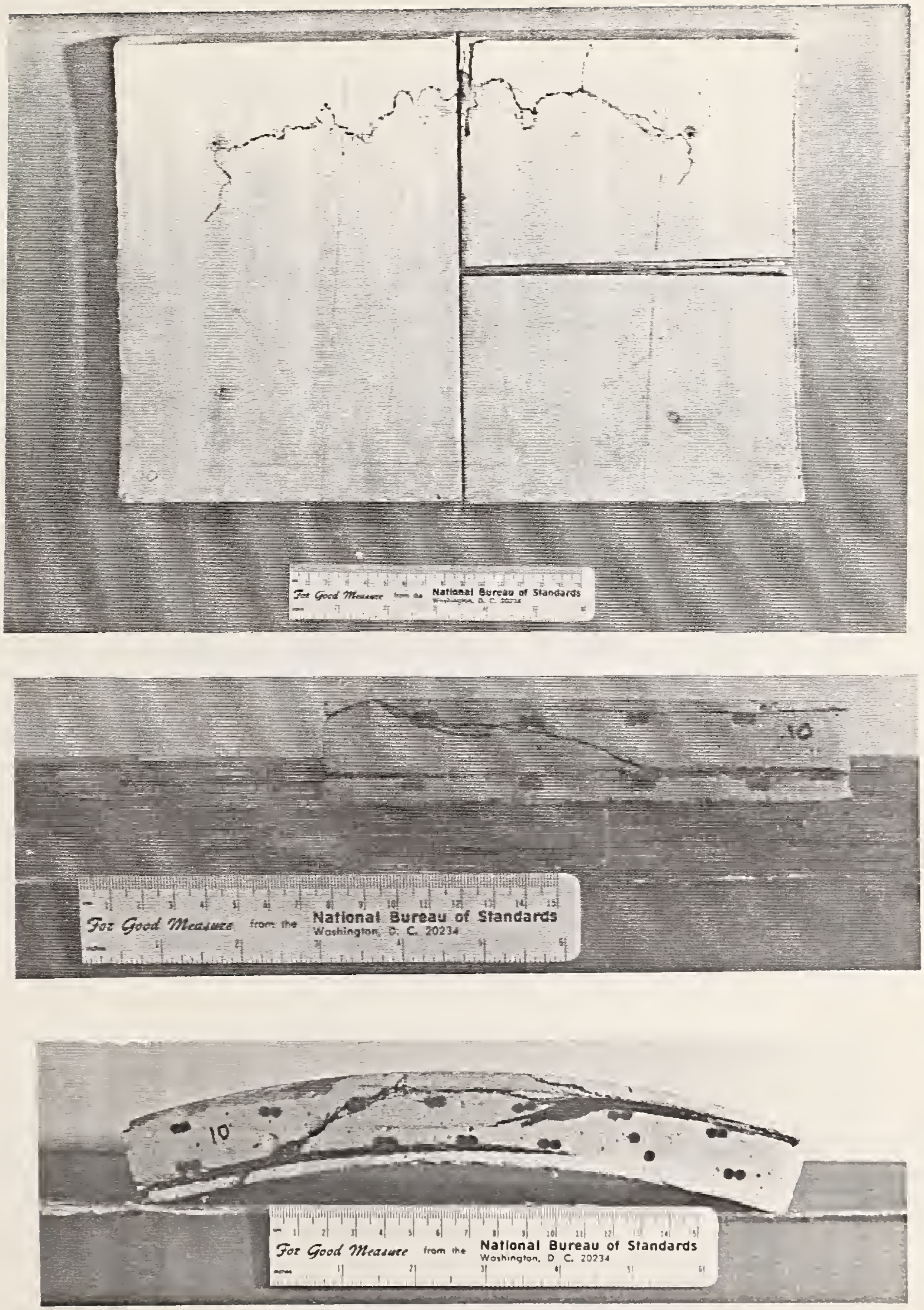


Fig. 4.10 Cracks in specimen no. 10: a) underside; b) transverse cross-section on half the specimen; and c) span cross-section.

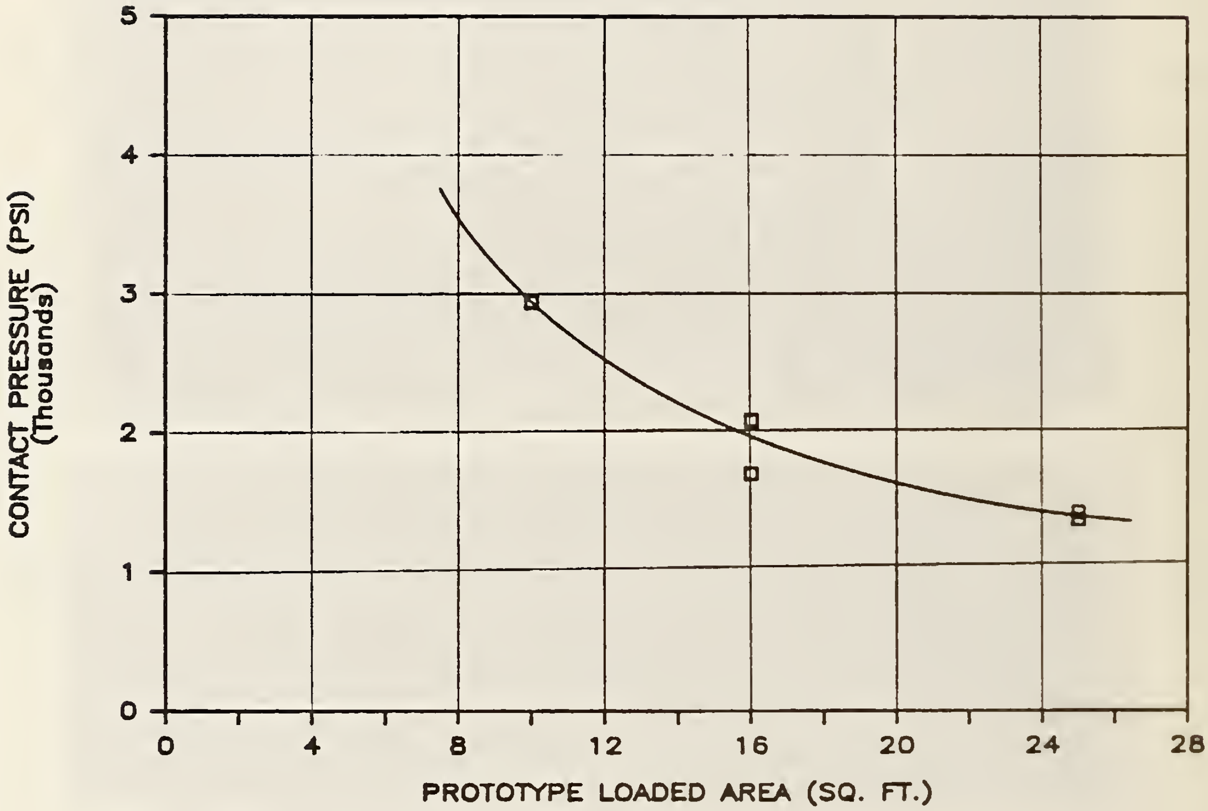


Fig. 4.11 Variation in contact pressure at the ultimate load with changes in the area of loading for the 1/25-scale plate specimens.

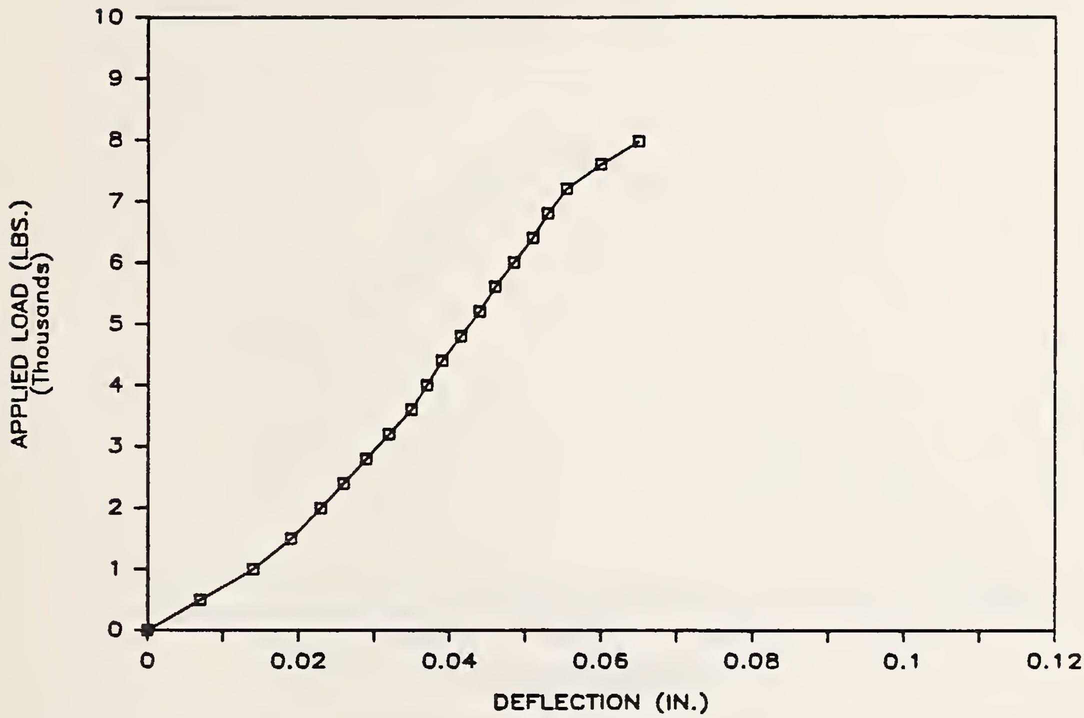


Fig. 4.12 Load-deflection curve for specimen no. 1.

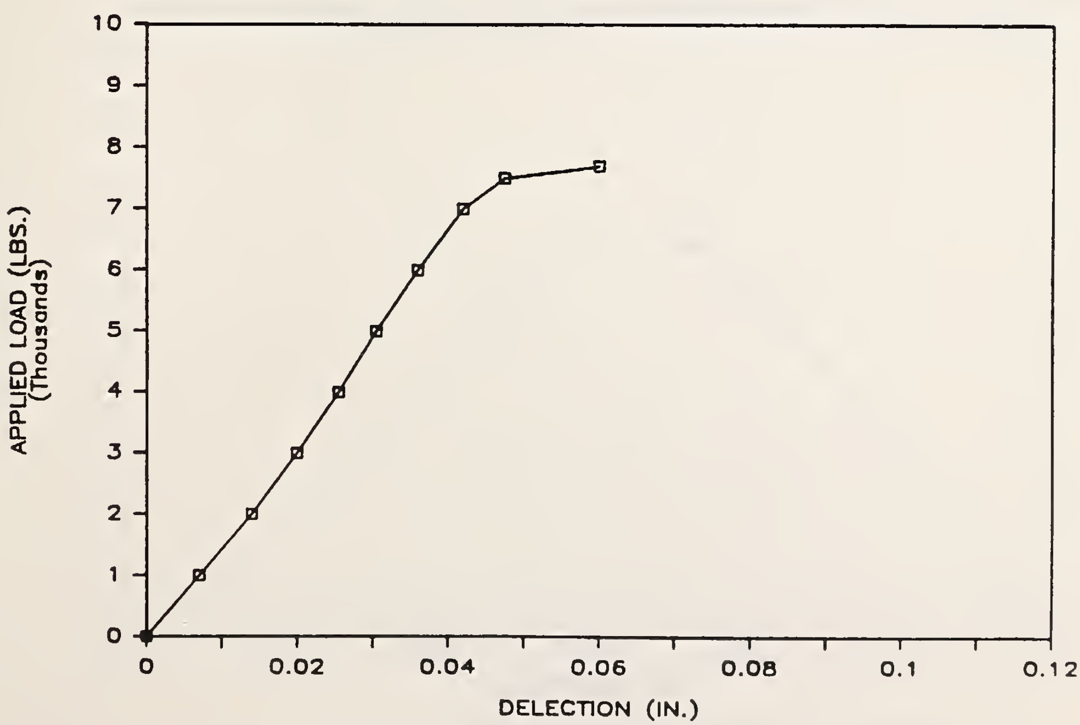


Fig. 4.13 Load-deflection curve for specimen no. 2.

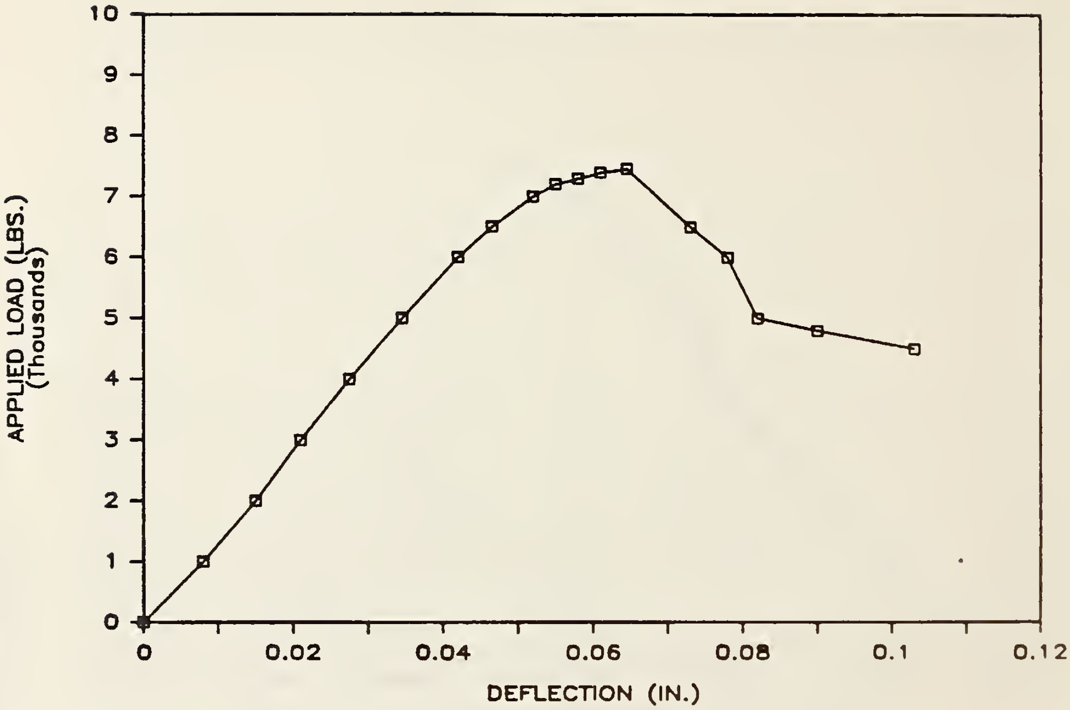


Fig. 4.14 Load-deflection curve for specimen no. 3.

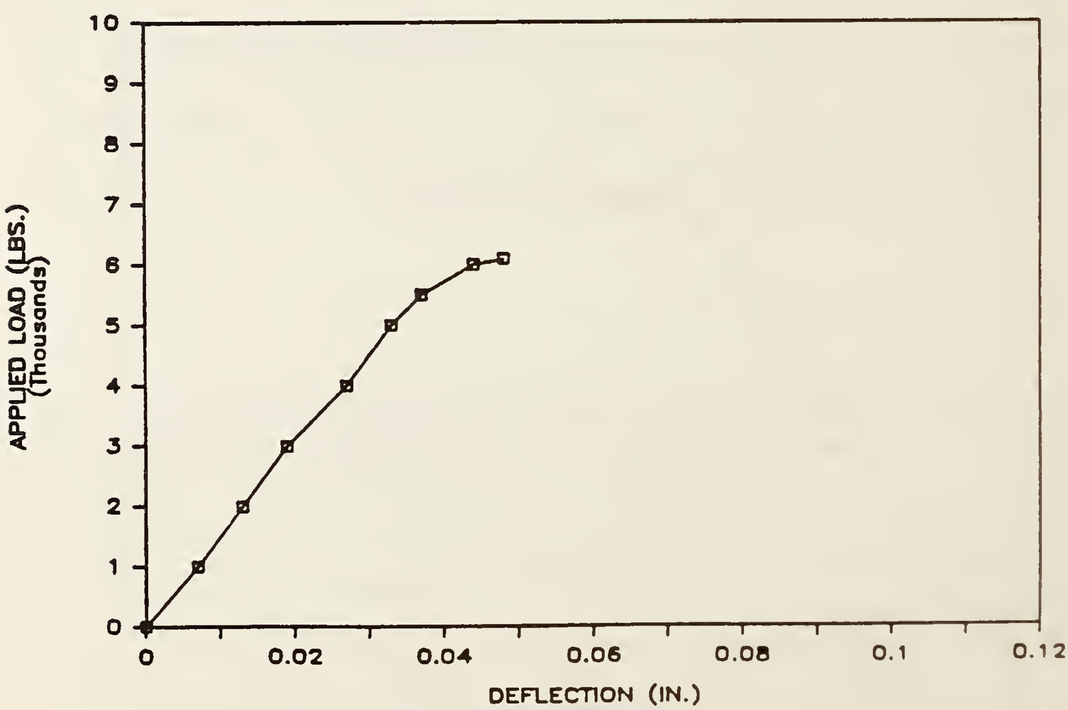


Fig. 4.15 Load-deflection curve for specimen no. 4.

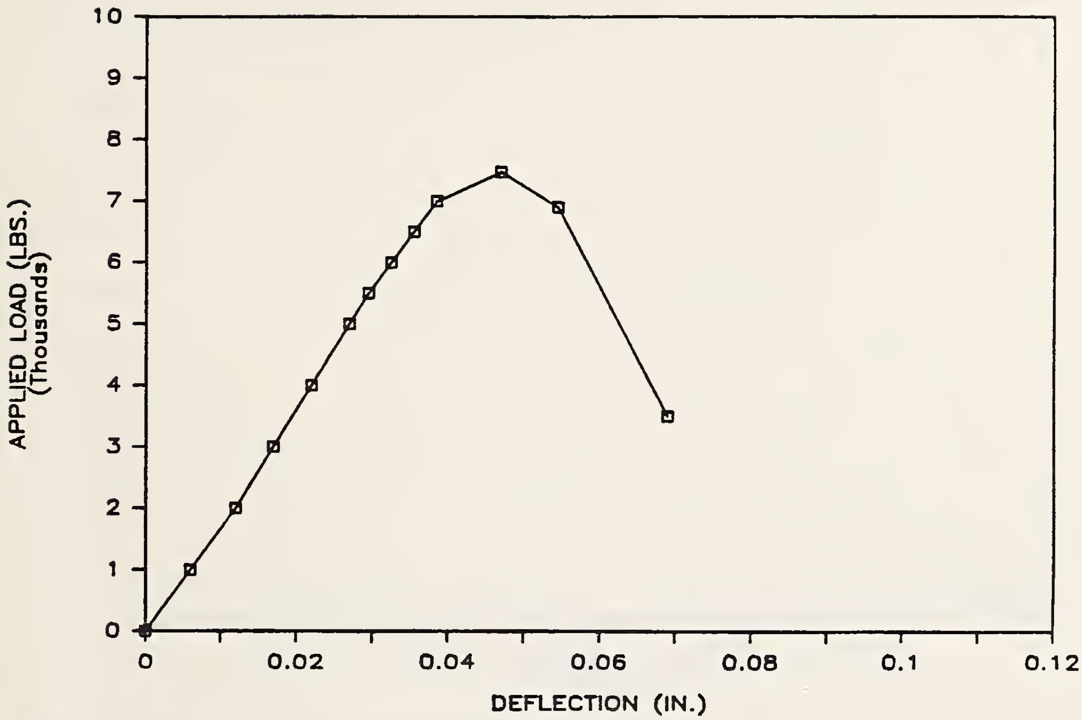


Fig. 4.16 Load-deflection curve for specimen no. 5.

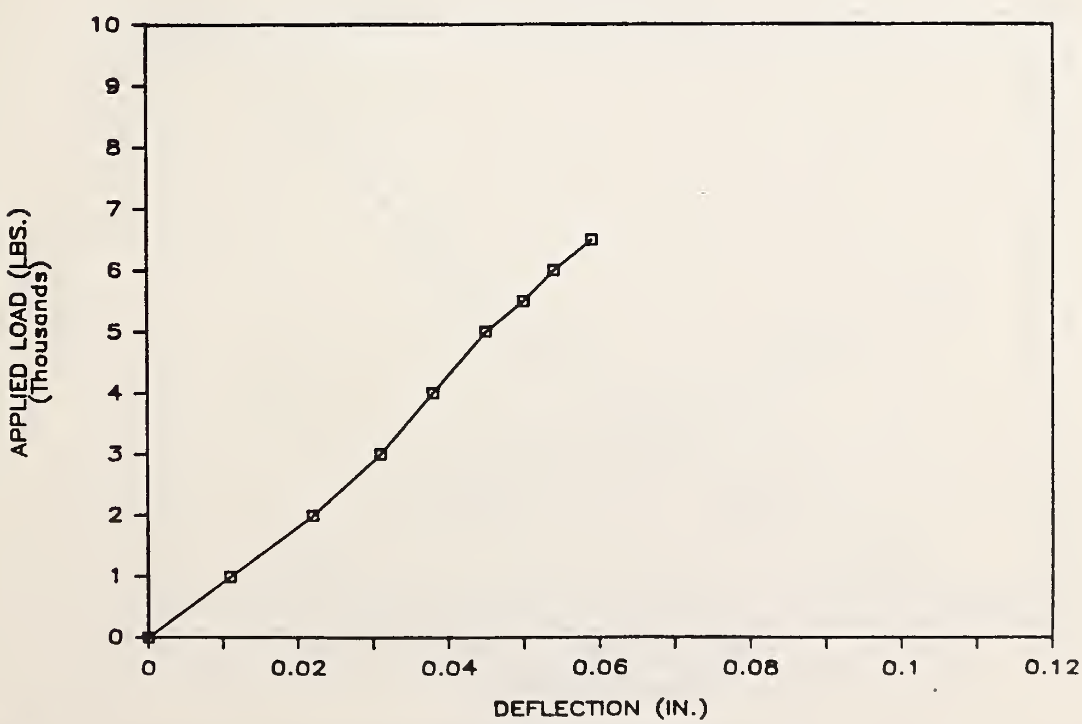


Fig. 4.17 Load-deflection curve for specimen no. 6.

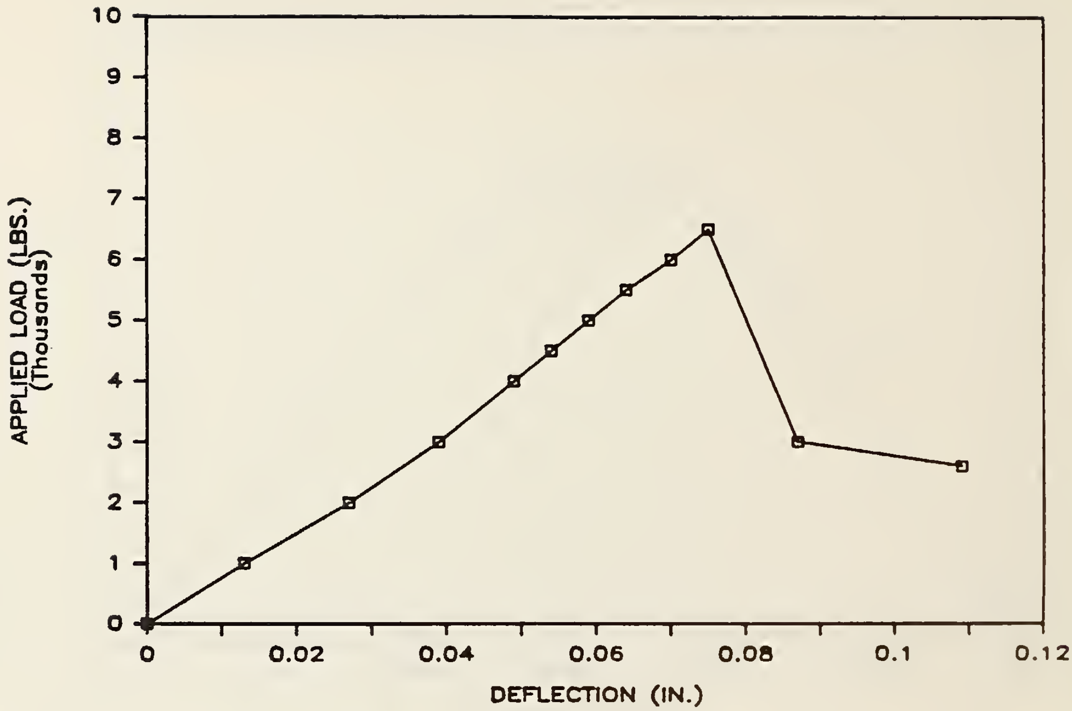


Fig. 4.18 Load-deflection curve for specimen no. 7.

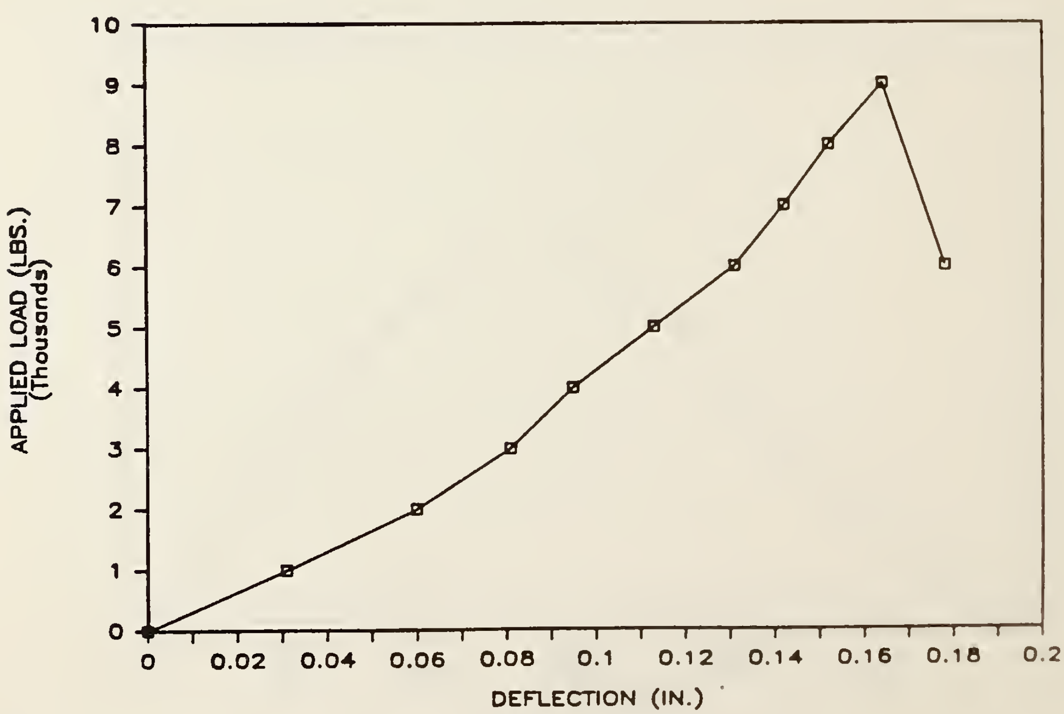


Fig. 4.19 Load-deflection curve for specimen no. 8.

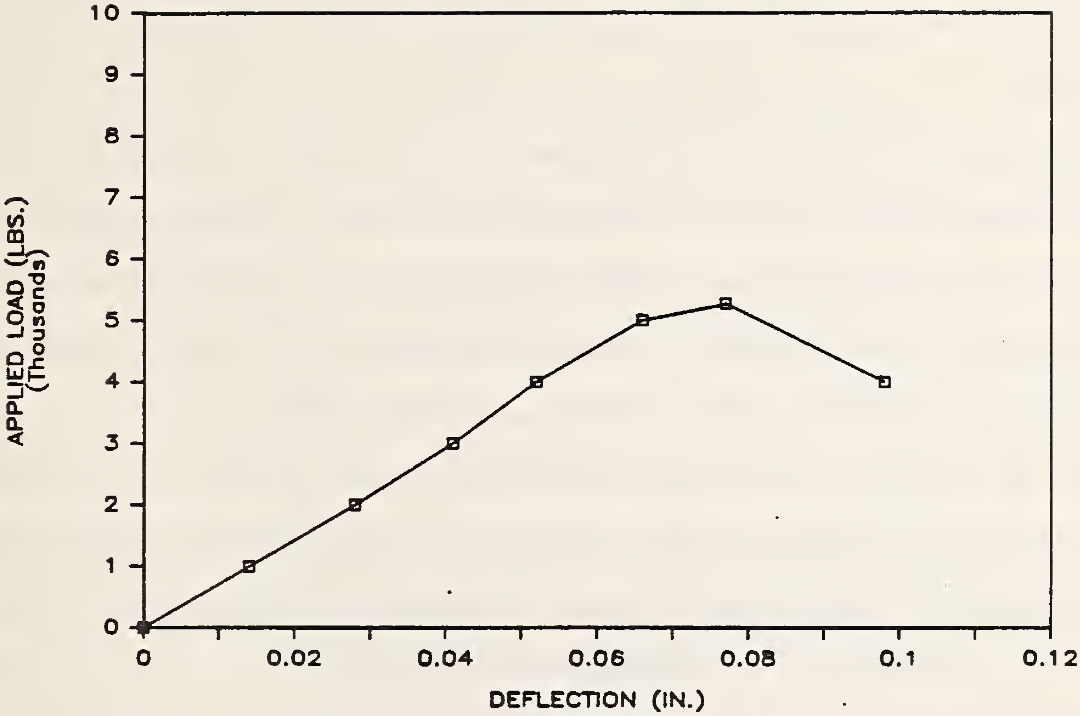


Fig. 4.20 Load-deflection curve for specimen no. 9.

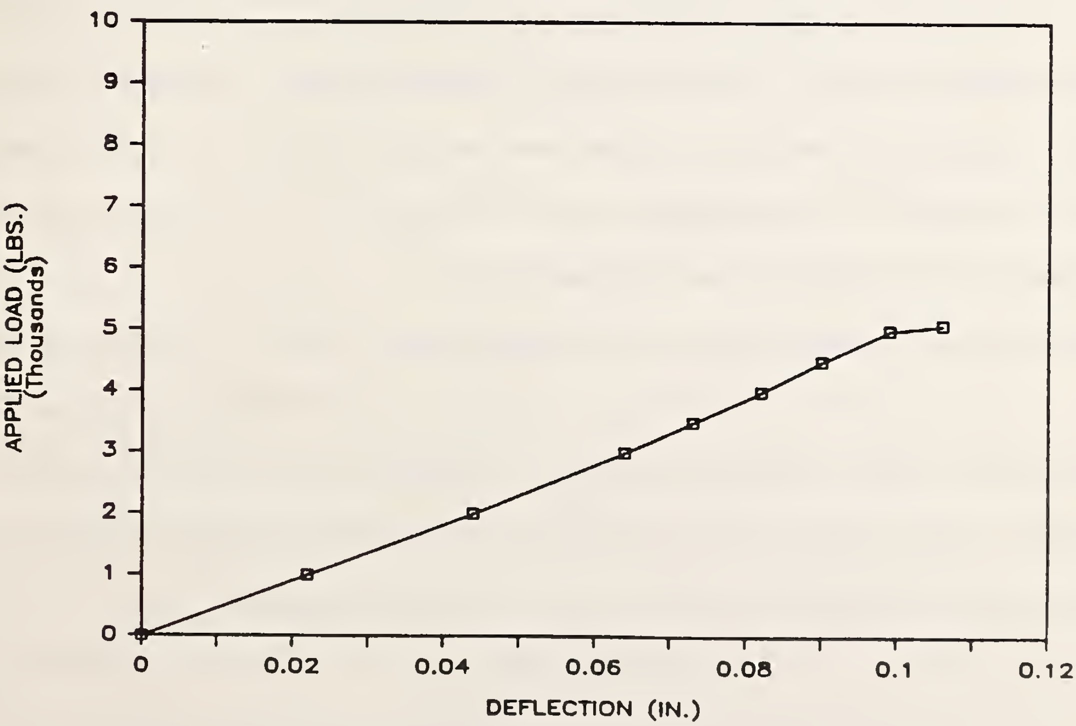


Fig. 4.21 Load-deflection curve for specimen no. 10.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 SUMMARY

This report presented the results of a 1/25-scale model study investigating punching shear failures in both plate and shell specimens. This study was undertaken to examine the effect of various parameters on punching shear behavior and to provide guidance for the selection of parameters for use in a larger, 1/6-scale, testing program.

Initial tests on 1/6-scale plate specimens resulted in a complex combined punching and beam shear failure, with the supports influencing crack development in the span direction and the cracks propagating out the sides of the specimens in the transverse direction.

It was seen that the 1/25-scale models were capable of qualitatively replicating the failure mechanism that occurred in the initial 1/6-scale plate tests. Using scaling laws, some quantitative agreement was also observed between the 1/25-scale and 1/6-scale tests. Parameters were adjusted in the 1/25-scale plate specimens until, in Specimen Nos. 6 and 7, failure was primarily in punching shear. Failure of shell Specimen Nos. 9 and 10 was also primarily in punching shear.

As shown by these tests, the punching shear behavior of plates and shells can be predicted qualitatively using 1/25-scale models. This ability to investigate the ultimate strength behavior of reinforced concrete structures using models is a valuable tool when available analytical techniques prove inadequate.

5.2 CONCLUSIONS AND RECOMMENDATIONS

As a result of this model study, several conclusions and recommendations for the 1/6-scale testing program are made.

1) Reducing the area of loading provided the most significant improvement towards reaching a clear-cut punching shear failure in the specimens. Based on the test results, it is recommended that an area of loading of 50 in^2 (corresponding to 12.5 ft^2 on a prototype structure) be used in the 1/6-scale model investigation. Using figure 4.11 to provide some measure of what the contact pressure would be with this area of loading, a value of 2300 psi is obtained, which is within the desired range of 500 to 3500 psi. Contact pressures in shear-reinforced and prestressed test specimens will be higher.

2) Reducing the flexural reinforcing ratio to 1.5 percent resulted in the shear cracks penetrating through the steel layers more easily, and no yielding of the reinforcement was apparent. It is recommended that a flexural reinforcing ratio of 1.75 percent be used in the 1/6-scale model investigation. The recommended value of 1.75 percent is slightly higher than the value of 1.5 percent used in the model tests to reflect the fact that specimens with shear reinforcement and prestressing, which will result in larger failure loads than observed in these specimens, are included in the testing program.

3) Finally, it is recommended that the thickness of the shell specimens in the 1/6-scale models be 5 in instead of the 7 in used for the plate specimens (corresponding to 30 in for the shells and 42 in for the plates in a prototype structure). This reduced thickness is still representative of Arctic offshore structures, and using the reduced thickness will result in a

more well-defined punching shear failure in the specimens. Referring to table 4.1, it should also be noted that the contact pressure for the shell specimen with the larger thickness was unrealistically high, while for the shells with the reduced thicknesses, the contact pressures were in the desired range of 500 to 3500 psi.

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2. Phan, L.T., Lew, H.S., and McLean, D.I., "Punching Shear Resistance of Lightweight Concrete Offshore Structures for the Arctic: Planning of Experimental Study," NBSIR 86-3440, National Bureau of Standards, Gaithersburg, Maryland, July, 1986.

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5. AUTHOR(S) David I. McLean, H.S. Lew, Long T. Phan, Hae I. Kim

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The punching shear resistance of lightweight concrete offshore structures for the Arctic is being investigated at the National Bureau of Standards on behalf of The Minerals Management Service of the U.S. Department of the Interior in cooperation with the following U.S. oil companies: Chevron Corporation, Exxon Production Research Company, Mobil Research and Development Corporation, and Sohio Petroleum Company. This report presents results of a 1/25-scale model study investigating the punching shear behavior of both plate and shell specimens. The study was undertaken to provide guidance for the selection of parameters for use in a larger, 1/6-scale, testing program. Initial tests on 1/6-scale plate specimens resulted in a complex combined punching and beam shear failure. The 1/25-scale models were capable of qualitatively replicating the failure mechanism that occurred in the initial 1/6-scale plate tests, and parameters were adjusted in the 1/25-scale specimens until a primarily punching shear failure was obtained in these specimens. Some quantitative agreement was also observed between the 1/25-scale and 1/6-scale tests. Recommendations are made for the 1/6-scale testing program.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Arctic environment; experimental investigation; lightweight concrete; offshore structure; punching shear; reinforced concrete; small-scale model.

13. AVAILABILITY

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